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DEVELOPMENT OF THE AERODYNAMIC/AEROSERVOELASTIC MODULES IN ASTROS

VOLUME 1: ZAERO USER'S MANUAL (F33615-96-C-3217)

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13. ABSTRACT (*Maximum 200 words*)

This report is a part of the documentations which describe the complete development of an STTR Phase II effort entitled, "Development of the Aerodynamic/Aeroservoelastic Modules in ASTROS." This report is one of four manuals that comprise the final report. The remaining reports consist of the ZAERO Programmer's Manual (Volume II), the ZAERO Applications Manual (Volume III) and the ZAERO Theoretical Manual (Volume IV).

ASTROS* is the seamless integration of the ZAERO module into ASTROS. As an aerodynamic enhancement to ASTROS, ZAERO is the ZONA aerodynamic module, unified for all Mach number ranges. This manual assumes the reader is familiar with the ASTROS system (Version 10.0), its terminology and user interface. It provides the complete user interface to the ASTROS* system required for preparation of input data.

First, an overview of the ZAERO software is presented. Second, the executive control options are described. Third, a complete and comprehensive description of the bulk data input is presented. Fourth, ZAERO modeling guidelines are provided with detailed descriptions for proper aerodynamic, geometry and spline input. Finally, the output description of ZAERO is presented with output samples.

14. SUBJECT TERMS

Multidisciplinary Optimization, ZAERO Module, ASTROS*, Subsonic-Transonic-Supersonic-Hypersonic Aerodynamics, Aeroelasity, Aeroservoelasticity, Flutter

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FOREWORD

This interim report is submitted in fulfillment of CDRL CLIN 0001, Data Item A008, Title: Software User Manual (USM) of a Small Business Technology Transfer (STTR) Phase II contract No. F33615-96-C-3217 entitled, "Development of the Aerodynamic/Aeroservoelastic Modules in ASTROS," covering the performance period from 24 September 1996 to 24 September 1998. This document provides the user's documentation for the ZAERO module in ASTROS*.

This work was performed by ZONA Technology, Inc. and its subcontractors, the University of Oklahoma (Research Institute)/Technion (I.I.T) and Universal Analytics Inc. This work is the second phase of a continuing two-phase STTR contract supported by AFRL/Wright-Patterson. The first phase STTR contract No. F33615-95-C-3219 entitled, "Enhancement of the Aeroservoelastic Capability in ASTROS," was completed in May 1996 and published as WL-TR-96-3119. Started in September 1996, the present second phase STTR contract was conducted by the same team members as in Phase I. These contributors are: P.C. Chen (P.I.), D. Sarhaddi and D.D. Liu of ZONA Technology Inc.; Fred Striz of the University of Oklahoma; Moti Karpel of Technion/I.I.T.; and Tony Shimko and Steve Chen of Universal Analytics.

At AFRL/Wright-Patterson, Capt. Gerald Andersen is the contract monitor and Dr. V.B. Venkayya is the initiator of the whole STTR effort. The technical advice and assistance received from Mr. Doug Niell of The MacNeal Schwendler Corporation, Dr. V.B. Venkayya and others from AFRL during the course of the present phase on the development of ASTROS* are gratefully acknowledged.

1.0 INTRODUCTION

There are four major documents that describe the ZONA Aerodynamics (ZAERO) Module which has been seamlessly integrated into the Automated STRuctural Optimization System (ASTROS). These are: the ZAERO User's, Programmer's, Application and Theoretical Manuals for ASTROS*. While ZAERO represents the ZONA Aerodynamics Module, ASTROS* is defined as the seamless integration of ZAERO into ASTROS, i.e. ASTROS* = ZAERO + ASTROS. This User's Manual provides the complete ZAERO user interface to the ASTROS* system required for preparation of input data.

This manual assumes that the reader is familiar with the ASTROS system (Version 11.0), its terminology and user interface. A complete and comprehensive description of the ASTROS environment can be found in the ASTROS User's and Programmer's Manuals (References: D.J. Neill, D.L. Herendeen, "ASTROS User's Manual," Volume I, WL-TR-96-3004, May 1995, D.J. Neill, D.L. Herendeen, R.L. Hoesly, "ASTROS Programmer's Manual," Volume II, WL-TR-93-3038, March 1993).

Section 2 presents an overview of the ZAERO software, its aerodynamic capability compared to that of the previous modules in ASTROS, and the program architecture of ZAERO and its integration into ASTROS.

Section 3 presents the ZAERO executive control discipline options, output request options, and restart capability.

Section 4 provides a complete description of the ZAERO bulk data input. This section presents a general overview of the ZAERO bulk data input used to define the aircraft geomerty along with the ZAERO and ASTROS bulk data interrelationships. Detailed bulk data descriptions are provided at the end of the chapter.

Section 5 covers important ZAERO modeling guidelines to avoid potential errors that may occur due to improper model setup.

Section 6 presents the ZAERO output descriptions for all discipline output requests. Numerous output samples and figures are provided.

2.0 ZAERO MODULE AND ASTROS*

ASTROS (Automated STRuctural Optimization System) is a finite element based procedure tailored for the preliminary design of aerospace structures. As such, it includes flexibility and generality in multiple discipline integration. For aircraft, missile or spacecraft design, the unique attributes of ASTROS lie in its savings of design effort and time, with an associated improvement in flight performance and reduction in structural weight. In principle, ASTROS was designed to effectively integrate multidisciplinary areas like aerodynamics, aeroelastics, and structures. Although today an aclaimed, well-proven tool for Multidisciplinary Optimization (MDO) and analysis, ASTROS still requires further improvement in its capabilities with respect to steady/unsteady aerodynamics, aeroelasticity and aeroservoelasticity (Reference: Johnson, E.H. and Venkayya, V.B., "Automated Structural Optimization System (ASTROS), Theoretical Manual," AFWAL-TR-88-3028, Vol. 1, December 1988).

The ZONA aerodynamic codes contained in the ZAERO module were exclusively developed by ZONA Technology. These include four major steady/unsteady aerodynamic codes, namely ZONA6, ZONA7, ZTAIC, and ZONA7U, that jointly cover the complete domain of all Mach number ranges. The ZONA aerodynamic system (the ZAERO System) which contains the ZAERO module and two other modules were developed under the support of AFRL/Wright-Patterson AFB to be seamlessly integrated into the ASTROS system to improve and enhance the aerodynamics, aeroelasticity and aeroservoelasticity (ASE) capability of ASTROS. In particular, the ZAERO module improves the aerodynamic capability over the earlier aerodynamic modules in ASTROS in the following respects (also see Figs 1 and 2):

1. Wing-Body geometry input for realistic aircraft configurations including external stores.
2. Flight regimes that include subsonic, supersonic, transonic and hypersonic Mach numbers.
3. High-order paneling scheme to assure accurate and robust solutions (without stringent paneling requirements).
4. Provides Aerodynamic Influence Coefficient (AIC) matricies for all flow regimes including the generation of transonic AIC.
5. Steady/unsteady aerodynamic options for static/dynamic aeroelastic applications.
6. Unified aerodynamic geometry bulk data input.
7. 3-D spline capability that includes the infinite plate spline method, beam spline method, thin plate spline method and rigid body attachment.

The development and seamless integration of the ZAERO System into ASTROS has created a unique Multidisciplinary Design/Analysis and Optimization (MDO/MAO) tool that is currently unsurpassed in its steady/unsteady aerodynamic and aeroelastic capability. The ZAERO System consists of essentially three modules which include the ZAERO module, the unified AGM (Aerodynamic Geometry) module and the 3D-Spline module (see Fig 3).

As can be seen in Fig 1, current capabilities of ASTROS and NASTRAN are limited to subsonic and supersonic Mach numbers and applicable to lifting surfaces only. By contrast, ZAERO is valid throughout the full range of subsonic to hypersonic Mach numbers and is applicable to complex aircraft configurations with external stores.

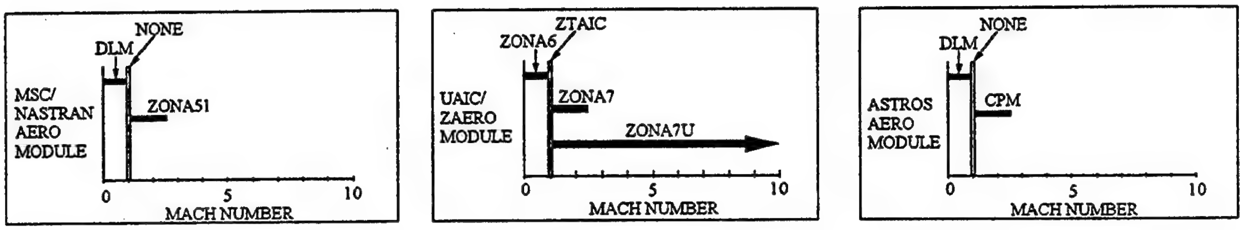

Figure 2.1 ZAERO and Other Aerodynamic Modules.

Fig 2 shows the capability of each code in the ZAERO Module (marked with †) along with other ZONA Codes.

Capability		ZONA Unsteady/Steady Aerodynamic Codes – ZAERO						
		ZONA51	*ZONA51U*	*ZONA7*†	*ZONA7U*†	*ZONA6*†	*ZTAIC*†	*ZTAIC6*
Geometry	• Lifting Surface (L.S.)	●	●	●	●	●	●	●
	• Thickness Effect		●		●		●	●
	• L.S. + Body = Whole Aircraft			●	●	●		●
Mach Number	• Subsonic					●	●	●
	• Transonic						●	●
	• Supersonic	●	●	●	●			
	• Hypersonic		●		●			

Figure 2.2 Capability of the ZONA Steady/Unsteady Aerodynamic Codes.

The seamlessly integrated ZAERO System in ASTROS is called ASTROS*. Fig 3 illustrates the role of the ZAERO System within ASTROS* and the overall ASTROS* program architecture. The ZAERO System consists of three primary modules with the following functionalities:

- *Unified Aerodynamic Geometry Module (AGM)*
  The Unified Aerodynamic Geometry Module processes the ZAERO model aerodynamic geometry input. Two newly created bulk data cards are used to define the aerodynamic geometry, namely **CAERO7** for wing-like components such as wings, tails, pylons, launchers and store fins, and **BODY7** for body-like components such as fuselage, stores and missile bodies.

- *3-D Spline Module*
  The 3-D Spline Module provides for the interconnection between the aerodynamic and structural models through the generation of a spline matrix. Four spline methods are supported by this module. These are the infinite plate spline (IPS) method (**SPLINE 1**), the beam spline method (**SPLINE 2**) and the thin plate spline (TPS) method (**SPLINE 3**) and the rigid body attachment method (**ATTACH**). The TPS is an addition to the spline capability provided by ASTROS and unlike the IPS method does not require that a spline plane be defined.

- *The ZAERO Module*
  The ZAERO Module is made up of the four major aerodynamic codes (ZONA6, ZONA7, ZTAIC, ZONA7U) and generates the Unified Aerodynamic Influence Coefficient (UAIC) matrices, gust force vectors, control surface aerodynamic vectors and steady aerodynamic force vectors of trim parameters.

Database entities generated by AGM, 3-D Spline and ZAERO modules are computed in the ASTROS* preface phase and are not recomputed in the analysis/optimization loop.

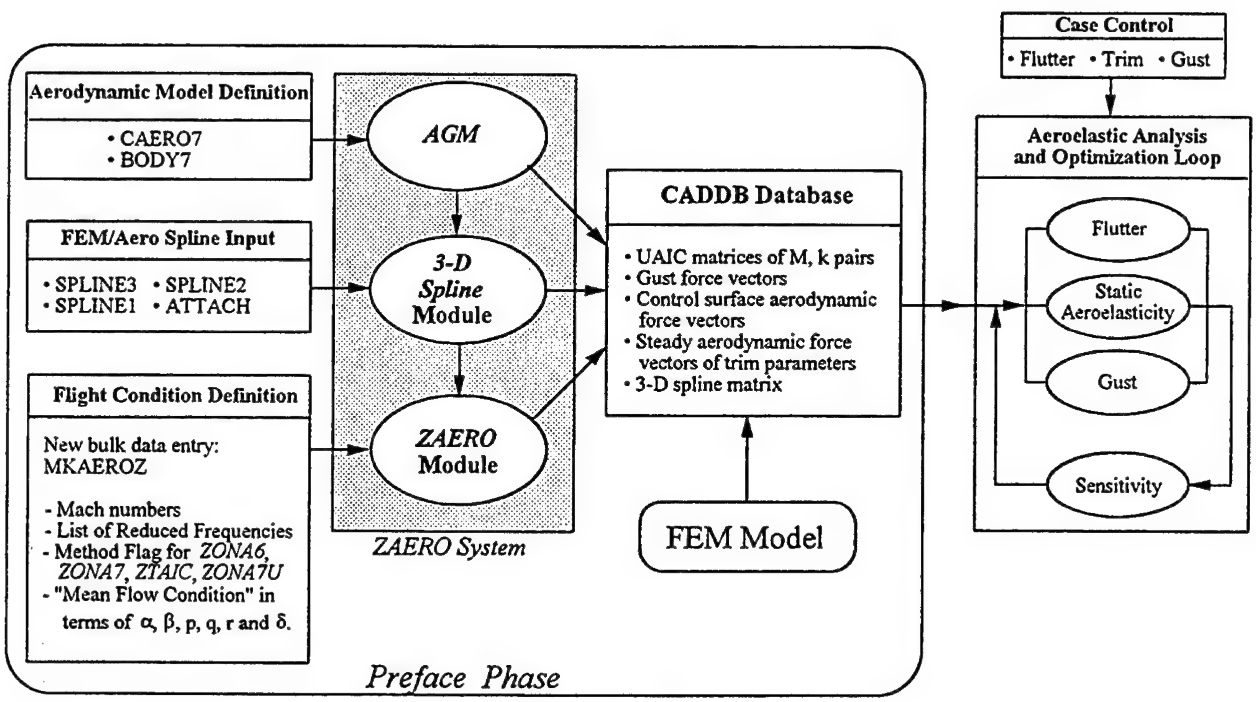

Figure 2.3 ASTROS/ZAERO (ASTROS*) Program Architecture.

3.0 ZAERO SOLUTION CONTROL

The ASTROS* solution control remains unchanged from that of ASTROS with the exception of the PRINT and PUNCH commands. Printing and punching subset aerodynamic options such as AIRD, QHH, QHJ and TPRE should not be used through the PRINT and PUNCH commands. Equivalent ZAERO output requests can be made through a simple switch setting in certain ZAERO bulk data inputs (see Section 3.2); otherwise, the solution control calls, used by ASTROS for the previous aerodynamics methods (i.e. Doublet-Lattice Method (DLM), Constant Pressure Method (CPM) and US Steady Aerodynamics(USSAERO)), such as FLUTTER and SAERO remain the same. The user is referred to the ASTROS User's Manual (D.J. Neill, D.L. Herendeen, "ASTROS User's Manual," Volume I, WL-TR-96-3004, May 1995) for a complete description of the ASTROS solution control.

3.1 ZAERO Solution Control Discipline Options

Previous aerodynamic methods available in ASTROS are inactive and have been replaced by ZAERO in ASTROS*. Solution control discipline requests that invoke the ZAERO methods are listed in Table XX.

Table 3.1 ZAERO Solution Control Disciplines

Solution Control Command	Description	Example
FLUTTER	Invokes the flutter discipline	FLUTTER (FLCOND=10)
SAERO	Invokes the static aerodynamics discipline	SAERO ANTISYMMETRIC (TRIM = 10)

3.2 ZAERO Output Requests

ZAERO output requests can be made through the **FLUTTER**, **MKAEROZ**, and **TRIM** bulk data cards through the PRINT flag entry. Table 3.2 presents the output request options for each of these cards.

Table 3.2 ZAERO Output Request Options.

Bulk Data Card	Output Options	Print Flag Value
FLUTTER	- no output - generalized aerodynamic forces - unsteady pressures on all aerodynamic boxes for all modes - flutter mode shapes on aerodynamic boxes	0 1, 2 or 3 2 or 3 3
MKAEROZ	- no output - aerodynamic pressure coefficients and stability derivatives of the rigid	0 ±1

	body motions (Symmetric Case: forward-aft translation, plunge and pitch motions; Antisymmetric Case: lateral translation, roll and yaw motions) - aerodynamic pressure coefficients, stability derivatives of the control surface motion and load modes - aerodynamic geometry data	 ±2 <0
TRIM	- no output - aerodynamic pressure coefficients and stability derivatives of the steady aeroelastic trim result - aerodynamic pressure coefficients and stability derivatives of the rigid body modes	0 ±1 ±2

A complete description of the output generated is presented in Section 6.0.

3.3 ZAERO Restart Capability

A restart-run capability has been implemented in ZAERO through the **MKAEROZ** bulk data card. The SAVE entry is used to specify whether to save the Aerodynamic Influence Coefficient (AIC) matricies of the current run (i.e. the current **MKAEROZ** card) or to read in a previously saved AIC file (i.e. the restart process). The filename to store the AIC's is specified by the FILENM entry which can be any alphanumeric string up to 16 characters long. The filename is automatically appended with the unique identification number of the corresponding **MKAEROZ** bulk data card. This allows the same AIC filename to be used in different **MKAEROZ** cards.

For example, the following MKAEROZ card

```
MKAEROZ 50      0.8     0               SAVE    F16CONFIG       -2      +MK1
+MK1    0.001   0.22    0.23    0.24    0.25    0.26    0.28    0.3     +MK2
+MK2    0.32    0.34    0.36    0.4     0.42    0.5     0.6     0.7     +MK3
+MK3    0.8     0.9     1.0
```

would save the AIC matricies to a file named

```
F16CONFIG.50
```

Each file saved via the **MKAEROZ** bulk data card will contain the AIC's for each Mach Number-Reduced Frequency (M-k) pair specified in the MACH and FREQi entries for both the symmetric and antisymmetric cases. (See **MKAEROZ** Bulk Data Card description).

3.4 ASTROS* Execution and Output Files

Execution of ASTROS* remains the same as that of ASTROS. A UNIX script file written in C shell script language controls the ASTROS* run. Execution syntax of ASTROS* is as follows:

```
#  astros  input.filename
```

where `astros` is the name of the ASTROS* script file and the *`input.filename`* is the ASTROS* input deck containing the solution control, bulk data, etc.

Output files generated by the script file are the ASTROS* output deck, logfile and a ZAERO punch file. The input.filename extension is replaced by (`.out`) and (`.log`) for the output deck and logfile, respectively. The punch file with a filename extension of (`.pch`) contains the aerodynamic model geometry generated by ZAERO in NASTRAN format that may be used for plotting.

The user is referred to the ASTROS User's Manual (D.J. Neill, D.L. Herendeen, "ASTROS User's Manual," Volume I, WL-TR-96-3004, May 1995) for a complete description of the ASTROS portion of the output deck including a description of the logfile output. The ZAERO portion of the output deck is described in Section 6.0.

4.0 ZAERO BULK DATA PACKET

4.1 ZAERO Geometry Input

The bulk data input developed for the ZONA Aerodynamics (ZAERO) module within ASTROS is substantially simpler to use than those utilized by other aerodynamic methods currently available in finite element programs in terms of the methodology used to input the aerodynamic geometry and the amount of data required to define a given configuration. ZAERO greatly reduces the burden to the user because of its capability to compute both unsteady and steady aerodynamics with a single input model. Previous aerodynamic methods within ASTROS required the input of both a steady and unsteady model through the use of different bulk data cards to define the same aerodynamic components, thereby greatly increasing the time spent by the user in generating the aerodynamic bulk data input.

The following figure shows the bulk data used to define the ZAERO geometry input and its relation to an aircraft configuration.

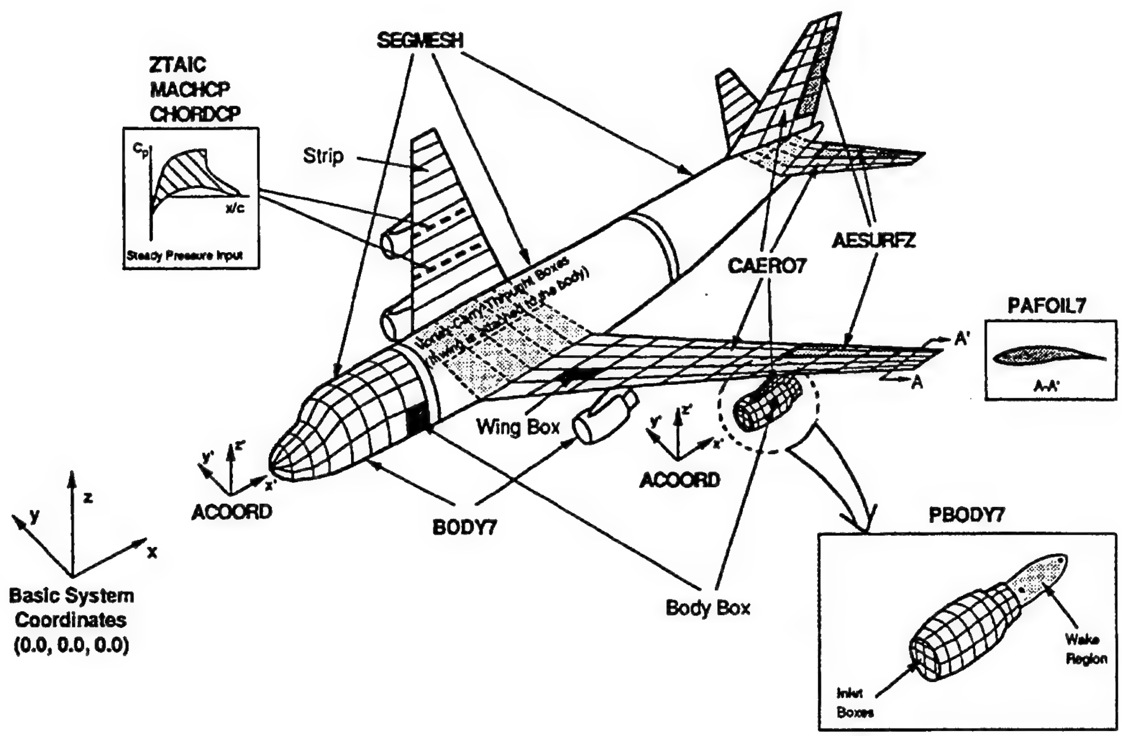

Figure 4.1 ZAERO Bulk Data Used to Define the Aerodynamic Geometry.

Two bulk data cards are used to completely define the aerodynamic model, namely, **CAERO7** for wing-like components such as wings, tails, pylons, launchers, store fins, etc., and **BODY7** for body-like components such as fuselage, engines, stores, etc. Body-like components can be subdivided into multiple segments (**SEGMESH** bulk data card) for cases where large discontinuities exist along the body shape such as the canopy region of a fighter aircraft or transition from circular fore sections of an aircraft to blended wing-body regions. The **SEGMESH**

allows for the segments to have varying numbers of chordwise and/or circumferential cuts along a given body where increased aerodynamic box density may be required. Both **CAERO7** and **BODY7** can be specified based on a local coordinate system defined by the **ACCORD** bulk data card. Control surfaces such as flaps, ailerons and rudders required for static aeroelastic analysis are defined by use of **AESURFZ** cards. Specification of body aerodynamic box inlet flow required for Superinclined Boxes such as engine inlets and/or wake conditions associated with truncated bodies are specified by **PBODY7** cards.

The two nonlinear aerodynamic methods incorporated within ZAERO (ZTAIC and ZONA7U, see Chapter 2.0) require additional input. The ZTAIC (transonic) method requires steady pressure input along lifting surface strips through the **ZTAIC**, **MACHCP** and **CHORDCP** bulk data input. The ZONA7U (hypersonic) method requires airfoil root/tip cross sections of lifting surfaces through PAFOIL7 cards.

4.2 ZAERO Bulk Data Interrelationships

Five flow charts are presented in Fig 4.2 showing all bulk data cards used by ZAERO. The flow charts are subdivided into five categories, namely, *Geometry*, *Disciplines*, *Structure-Aerodynamic Box Interconnection*, *Flight Parameters* and *Other*. Bulk data presented in bold face text belong to the ZAERO bulk data set, while text of unbold type is a part of the ASTROS bulk data set. The flow charts demonstrate the complete interconnection of all the ZAERO bulk data.

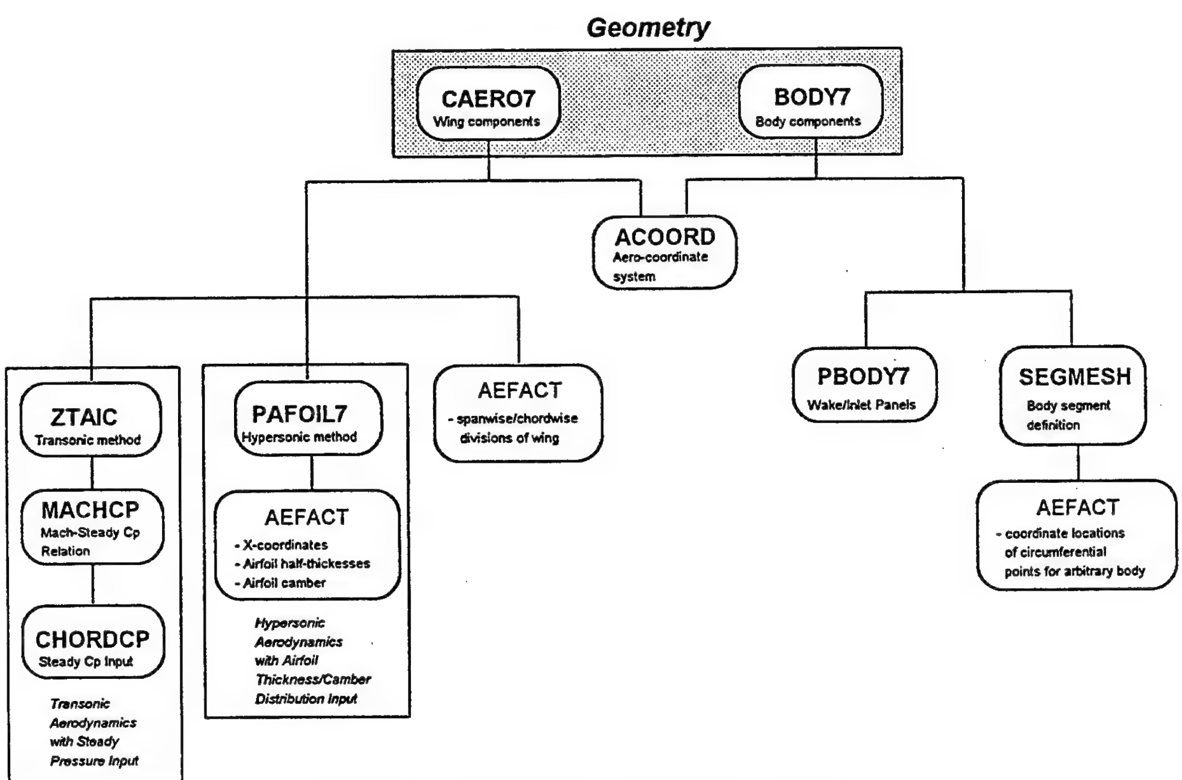

Figure 4.2. ZAERO Bulk Data Interconnection.

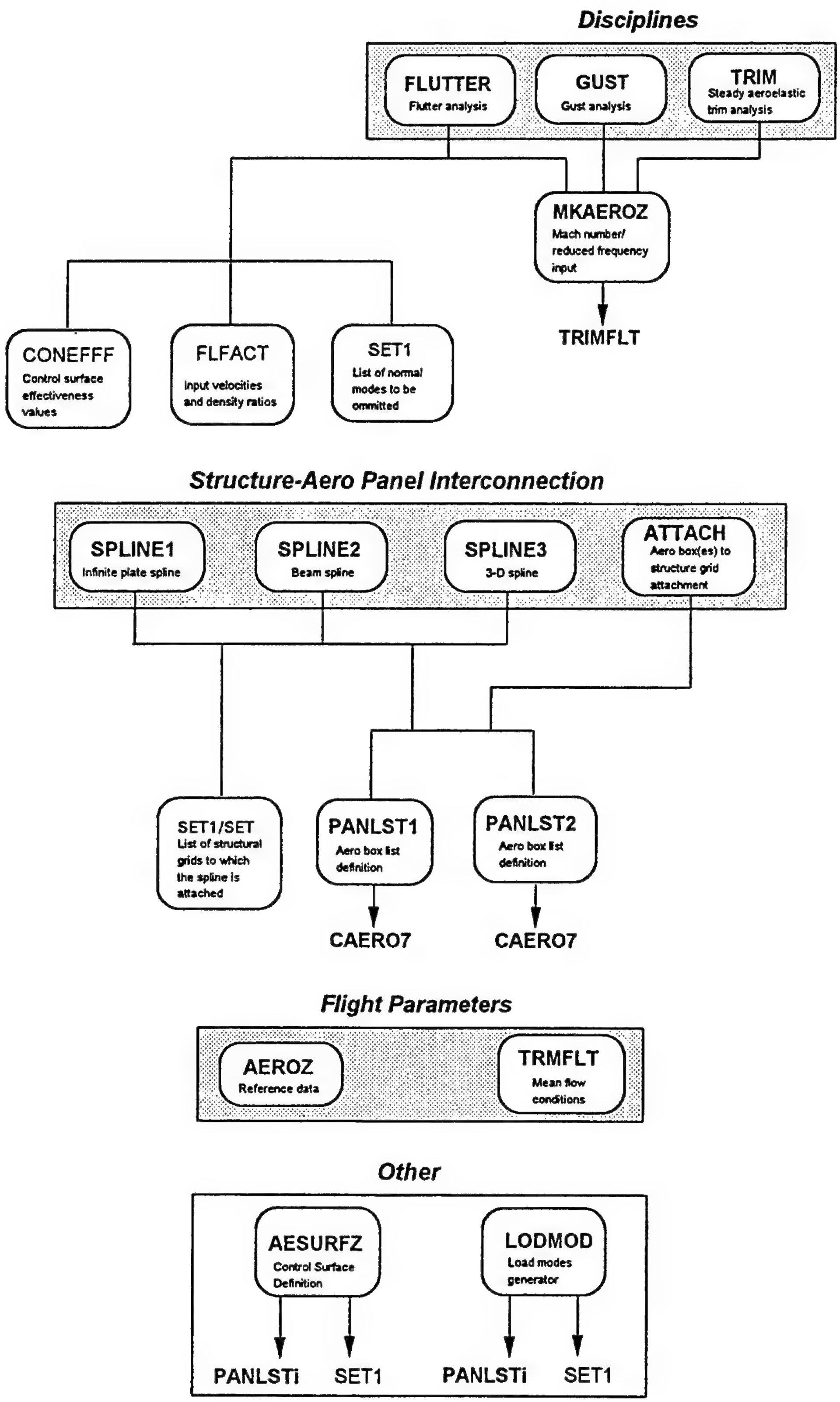

Figure 4.2 ZAERO Bulk Data Interconnection.

4.3 Bulk Data Summary

Twenty three bulk data cards are used to define the ZAERO input and are shown in Table XX.

Table 4.1 ZAERO Bulk Data Cards.

ZAERO Bulk Data Card	Description
ACOORD	Aerodynamic coordinate system definition.
AEROZ	Basic aerodynamic reference parameters.
AESURFZ	Aerodynamic control surface definition.
ATTACH	Defines a connection between aerodynamic box(es) and a reference grid point for spline.
BODY7	Aerodynamic body geometry input.
CAERO7	Aerodynamic lifting surface geometry input.
CHORDCP	Lifting surface steady pressure input for the ZTAIC (transonic) method.
FLUTTER	Defines data to perform flutter analysis.
GUST	Defines data to perform gust analysis.
LOADMOD	Defines a load mode of a set of structural grid points for computing component loads.
MACHCP	Establishes link between steady pressure input and Mach number for the ZTAIC (transonic) method.
MKAEROZ	Mach number and reduced frequency input for ZAERO steady/unsteady aerodynamics.
PAFOIL7	Defines airfoil cross sections at the root and tip for the ZONA7U (supersonic-hypersonic) method.
PANLST1	Defines a set of aerodynamic boxes (region defined by 2 aero box id's).
PANLST2	Defines a set of aerodynamic boxes (region defined by individual aero box id's).
PBODY7	Aerodynamic body wake and/or inlet aero box definition.
SEGMESH	Defines a mesh grid system for a body segment.
SPLINE1	Defines a surface spline for displacements and loads transfer between structural and aero models (infinite plate spline method).
SPLINE2	Defines a beam spline for displacements and loads transfer between structural and aero models.
SPLINE3	Defines a 3-D spline for displacements and loads transfer between structural and aero models (thin plate spline method).
TRIM	Specifies conditions for steady aeroelastic trim analysis.
TRIMFLT	Specifies mean flow conditions of steady and unsteady aerodynamics.
ZTAIC	Defines bulk data cards (MACHCP) to be used for sectional steady pressure input required by the ZTAIC (transonic) method.

4.4 Bulk Data Descriptions

The ZAERO bulk data format and data field formats remain unchanged from those of ASTROS. The user is referred to the ASTROS User's Manual (D.J. Neill, D.L. Herendeen, "ASTROS User's Manual," Volume I, WL-TR-96-3004, May 1995) for a complete description of the bulk data card format.

This section contains a complete description of each ZAERO bulk data card.

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Input Data Card: **ACOORD** ZONA Aerodynamic Coordinate System

Description: Defines a local coordinate system for an aerodynamic component referenced by the **BODY7** or **CAERO7** bulk data cards.

Format and Example:

1	2	3	4	5	6	7	8	9	10
ACOORD	ID	XORIGN	YORIGN	ZORIGN	DELTA	THETA	XMCNT	YMCNT	CONT
CONT	ZMCNT	XBEND	YBEND	ZBEND	XTORQ	YTORQ	ZTORQ		

ACOORD	10	250.0	52.5	15.0	0.0	0.0	300.0	52.5	ABC
+BC	15.0	310.0	52.5	15.0	310.0	95.0	15.0		

Field	Contents
ID	Coordinate system identification number (Integer > 0)
XORIGN YORIGN ZORIGN	X , Y, and Z location of the component origin (Real)
DELTA	Pitch angle in degrees measured from the X-Z axes of the basic coordinate system to the X'-Z' axes of the component coordinate system, positive in direction shown (see Remark 4 figure). This parameter will not physically rotate the model. Its effects are introduced in the boundary condition. Therefore, **DELTA** must be a small value. (Real) (See Remark 4)
THETA	Roll angle in degrees measured from the Y-Z axes of the basic coordinate system to the Y'-Z' axes of the component coordinate system, positive in direction shown (see Remark 4 figure). Unlike **DELTA, THETA** will physically rotate the model. (Real)
XMCNT YMCNT ZMCNT	Pitch and yaw moment center used only for calculating the pitch and yaw moments of the component (Real)
XBEND YBEND ZBEND	X, Y, and Z location of a point defining a vector from the pitch and yaw moment center about which a bending moment is computed (Real) (See Remark 5)
XTORQ YTORQ ZTORQ	X, Y, and Z location of a point defining a vector from the pitch and yaw moment center about which a torque is computed (Real) (See Remark 5)

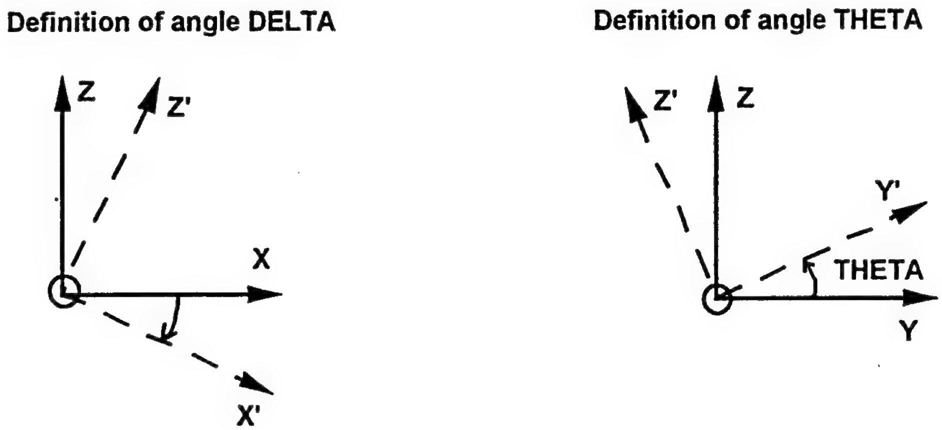
Remarks:

1. Coordinate system identification numbers (ID) on all **ACOORD** bulk data cards must be unique.

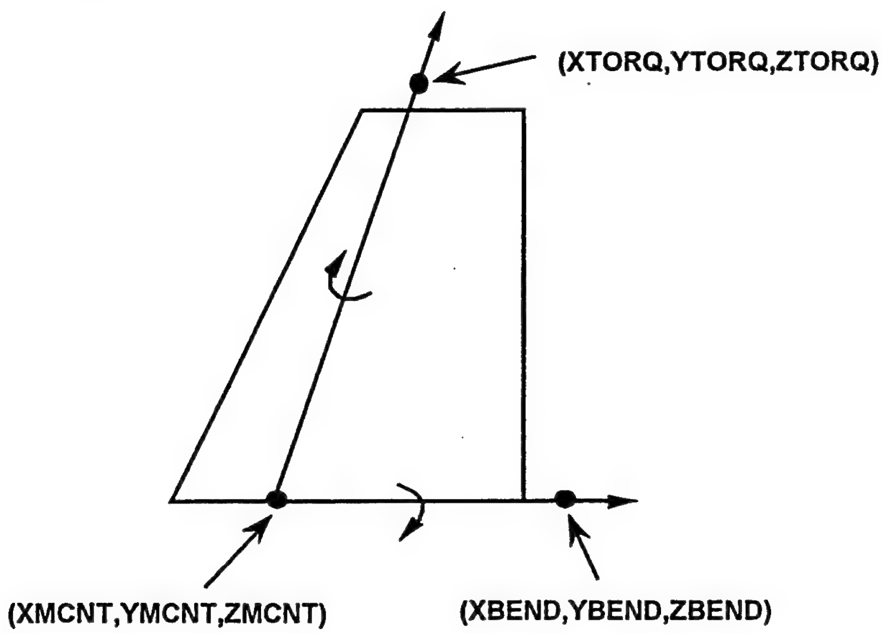
2. If **ACOORD** is referenced by a **BODY7** Bulk data card, the X-axis of the coordinate system defines the centerline of the body.

3. All coordinate locations are with reference to the basic coordinate system. **ACOORD** defines a rectangular coordinate system whose X-axis must be parallel to the X-axis of the basic coordinate system.

4. Since most underwing stores have a small inclination angle to the free stream, **DELTA** can be used to provide a simpler means for defining this inclination.



5. The **(X,Y,Z)MCNT, (X,Y,Z)BEND,** and **(X,Y,Z)TORQ** entries allow for the definition of two vectors about which the moments generated by the **BODY7** and/or **CAERO7** bulk data cards (that refer to the current **ACOORD** bulk data card) will be computed. As demonstrated in the following figure, bending moments about the wing root and torque about the wing quarter-chord are computed. The normal force is also computed along the resultant vector from the cross product of **(X,Y,Z)BEND** vector to **(X,Y,Z)TORQ** vector.



Input Data Card: **AEROZ** ZAERO Module Physical Data

Description: Gives the basic aerodynamic parameters for the ZAERO module.

Format and Example:

1	2	3	4	5	6	7	8	9	10
AEROZ	ACSID	XZSYM	RHOREF	REFC	REFB	REFS	GREF		

AEROZ	1	YES	.11E-07	20.0	40.0	400.0	300		

Field	Contents
ACSID	Identification number of a rectangular coordinate system in which the flow is in the positive x-direction and the pilot's right hand side is the positive y-direction (Integer > 0 or < 0 or blank) (See Remark 2)
XZSYM	Character string, either "YES" or "NO"; = YES the aerodynamic model is symmetric about its X-Z plane (this implies that only the half model on the right hand side is described), = NO both the right and left hand sides of the aircraft are modeled. (Character) (See Remark 3)
RHOREF	Reference density (Real ≥ 0) (See Remark 4)
REFC	Reference chord length (Real ≥ 0) (See Remark 5)
REFB	Reference span length (Real ≥ 0) (See Remark 5)
REFS	Reference area (Real ≥ 0) (See Remark 5)
GREF	Reference grid point ID for stability derivative calculation (Integer ≥ 0)

Remarks:

1. This card is required for the ZAERO module for both steady and unsteady aerodynamics. Only one **AEROZ** is allowed.

2. The ZAERO module assumes that the flow is in the positive X-direction in the basic coordinate system and that the aerodynamic model is on the right hand side of the X-Z plane (i.e. positive Y-direction). However, the structural model may be oriented in an arbitrary coordinate system. For splining the displacements and loads between the ZAERO and structural models the structural grid must first be transformed by the coordinate system **ACSID**. It is possible that the structural model may be located on the left hand side (i.e. negative Y-axis) of the coordinate system **ACSID**. In this situation, **ACSID** must be a negative integer (its absolute value represents the identification number of the rectangular coordinate system) and the structural model will be flipped from the left to the right hand side.

3. For a symmetric model (about the X-Z plane), the ZAERO module generates the symmetric and antisymmetric aerodynamic influence coefficient matrices simultaneously for all Mach numbers specified in the **MKAEROZ** and **TRIM** bulk data cards.

4. The density ratios specified in **FLUTTER** and **TRIM** bulk data cards need to be multiplied by **RHOREF** to obtain the values of air density.

5. For unsteady aerodynamics, the reduced frequency (k) is defined as

$$k = \frac{\omega\left(\frac{REFC}{2}\right)}{V_\infty}$$ where V_∞ is the free stream velocity and ω is the harmonic frequency in rad/sec.

For steady aerodynamics, the non-dimensional aerodynamic force and moment coefficients are defined as:

Lift Coefficient $C_L = \frac{L}{q_\infty (REFS)}$, L is the lift force

Drag Coefficient $C_D = \frac{D}{q_\infty (REFS)}$, D is the drag force

Pitch Moment Coefficient $C_M = \frac{M}{q_\infty (REFS)(REFC)}$, M is the pitch moment

Side Force Coefficient $C_Y = \frac{Y}{q_\infty (REFS)}$, Y is the side force

Roll Moment Coefficient $C_l = \frac{l}{q_\infty (REFS)(REFB)}$, l is the roll moment

Yaw Moment Coefficient $C_n = \frac{N}{q_\infty (REFS)(REFB)}$, N is the yaw moment

6. GREF specifies the ID of a **GRID** bulk data card whose X, Y and Z location defines the moment center for all aerodynamic moment calculations.

Input Data Card: **AESURFZ** ZONA Control Surface Definition

Description: Species an aerodynamic control surface for the ZAERO module.

Format and Example:

1	2	3	4	5	6	7	8	9	10
AESURFZ	LABEL	TYPE	CID	SETK	SETG				

AESURFZ	RUDDER	ASYM	1	10	20				

Field	Contents
LABEL	Unique alphanumeric string of up to eight characters used to identify the control surface (Character) (See Remark 2)
TYPE	Type of surface (Character) SYM symmetric surface ANTISYM antisymmetric surface ASYM asymmetric surface
CID	Identification number of a rectangular coordinate system whose Y-axis defines the hinge line of the control surface (Integer > 0 or blank)
SETK	Identification number of **PANLST1** or **PANLST2** bulk data card used to identify the aerodynamic box ID's of the control surface (Integer > 0) (See Remark 3)
SETG	Identification of **SET1** bulk data card used to identify the structural grid ID's of the control surface (Integer > 0 or blank) (See Remark 4)

Remarks:

1. **AESURFZ** is required for the steady **TRIM** and **ASE** modules.
2. The **LABEL** is arbitrary, but all labels must be unique.
3. The aerodynamic box numbering schemes are illustrated in the **CAERO7** and **BODY7** bulk data cards.
4. **SETG** is only required for the ASE module. It is used to compute the flap motion of the G-set degrees of freedom.

Input Data Card: **ATTACH** ZONA Aerodynamic Box-To-Grid Spline Attachment

Description: Defines aerodynamic box(es) to be attached to a reference grid for splining.

Format and Example:

1	2	3	4	5	6	7	8	9	10
ATTACH	EID	MODEL	SETK	REFGRID					

ATTACH	1	WING	10	3					

Field	Contents
EID	Element identification number (Integer > 0) (See Remark 2)
MODEL	NOT USED
SETK	Identification number of **PANLST1** or **PANLST2** bulk data card used to identify the aerodynamic box ID's (Integer > 0)
REFGRID	Reference grid point identification number (Integer > 0) (See Remark 3)

Remarks:

1. For an aerodynamic component not represented in the structural model, **ATTACH** is used to translate the displacements and loads between a structural grid point and the aerodynamic component.
2. **EID** is only used for error messages.
3. The translational and rotational degrees of freedom at the reference grid point defines a rigid body type of motion of the aerodynamic component.

Input Data Card: **BODY7** ZONA Unsteady Aerodynamic Body Component

Description: Defines an aerodynamic body macroelement for ZONA6 (subsonic), ZTAIC (transonic), ZONA7(supersonic), and ZONA7U(supersonic-hypersonic) aerodynamics.

Format and Example:

1	2	3	4	5	6	7	8	9	10
BODY7	BID	LABEL	IPBODY7	ACOORD	NSEG	IDMESH1	IDMESH2	IDMESH3	CONT
CONT	IDMESH4	-etc-							

BODY7	4	BODY	2	8	4	20	21	22	ABC
+BC	23								

Field	Contents
BID	Body identification number (Integer > 0)
LABEL	An arbitrary character string (up to 8 characters) used to define the body (Character)
IPBODY7	Identification number of **PBODY7** (specifying body wake and/or inlet aero boxes) bulk data card (Integer ≥ 0 or blank, Default = 0) (See Remark 1)
ACOORD	Identification number of **ACOORD** (specifying body center line location and orientation) bulk data card (Integer ≥ 0 or blank, Default = 0) (See Remark 2)
NSEG	Number of body segments (11 ≥ Integer > 0)
IDMESHi	Identification number of **SEGMESH** (specifying body segment aero box cuts) bulk data card (Integer > 0) (See Remark 4)

Remarks:

1. If **IPBODY7** is zero or blank, no **PBODY7** bulk data cards are needed.
2. The X-axis specified by the **ACOORD** bulk data card defines the centerline of the body macroelement. If **ACOORD** is zero, the X-axis of the basic coordinate system is used.
3. One **BODY7** may have many segments. Each segment consists of a mesh of grids that define the body boxes.
4. There must be **NSEG** numbers of **IDMESHi** input (i.e. **IDMESHi**, i=1,NSEG). Maximum value of NSEG=11.
5. **BODY7** generates a set of body boxes and grids. The identification numbers of these body boxes and grids are numbered sequentially beginning with BID.

Input Data Card: **CAERO7** ZONA Unsteady Aerodynamic Wing Component

Description: Defines an aerodynamic wing macroelement for ZONA6 (subsonic), ZTAIC (transonic), ZONA7 (supersonic), and ZONA7U (supersonic-hypersonic) aerodynamics.

Format and Example:

1	2	3	4	5	6	7	8	9	10
CAERO7	WID	LABEL	ACOORD	NSPAN	NCHORD	LSPAN	ZTAIC	PAFOIL7	CONT
CONT	XRL	YRL	ZRL	RCH	LRCHD	ATTCHR			CONT
CONT	XTL	YTL	ZTL	TCH	LTCHD	ATTCHT			

CAERO7	101	WING	8	5	4	20	0	0	ABC
+BC	0.0	0.0	0.0	1.0	10	4			DEF
+EF	0.0	1.0	0.0	1.0	11	0			

Field	Contents
WID	Wing identification number (Integer > 0)
LABEL	An arbitrary character string (up to 8 characters) used to define the wing (Character)
ACOORD	Identification number of **ACOORD** (specifying a local coordinate system and orientation) bulk data card (Integer ≥ 0 or blank, Default = 0)
NSPAN	Number of spanwise divisions of wing component (Integer ≥ 2)
NCHORD	Number of chordwise divisions of wing component (Integer ≥ 2)
LSPAN	Identification number of **AEFACT** bulk data card used to specify the spanwise divisions of the wing component in percentage of the wing span. The number of values listed in **AEFACT** must be NSPAN. If LSPAN = 0, then NSPAN evenly distributed spanwise divisions are used. (Integer ≥ 0) (See Remark 2)
ZTAIC	Identification number of a **ZTAIC** bulk data card; used <u>only</u> for the transonic aerodynamics (i.e. ZTAIC method) to specify sectional steady pressure input (Integer ≥ 0)
PAFOIL7	Identification number of a **PAFOIL7** bulk data card; used <u>only</u> for the supersonic/hypersonic aerodynamics (i.e. ZONA7U method) to specify sectional airfoil coordinates. If **PAFOIL7** = 0, it is assumed that the **CAERO7** wing component is a flat plate. (Integer ≥ 0)
XRL YRL ZRL	X, Y, and Z location of the root chord leading edge (Real)
RCH	Length of root chord (Real)

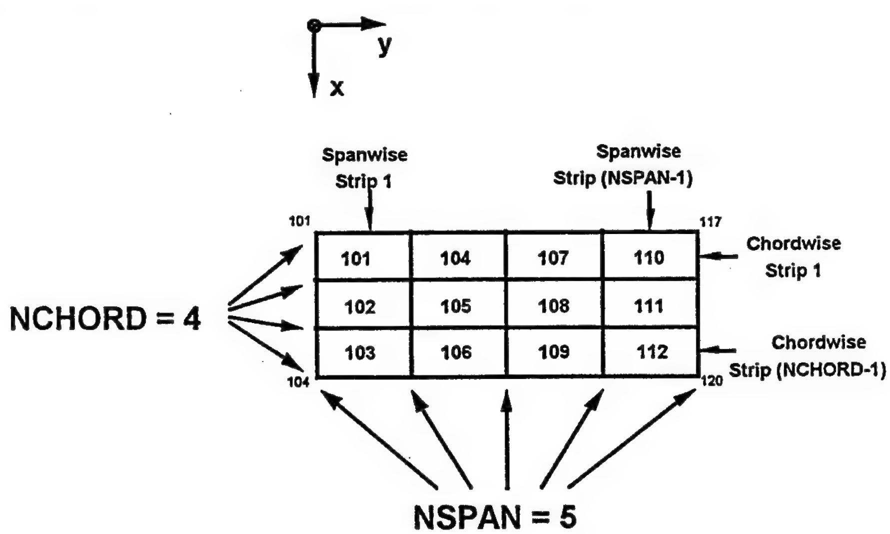
LRCHD	Identification number of **AEFACT** bulk data card used to specify the root chord divisions of the wing component in percentage of the root chord. The number of values listed in **AEFACT** must be NCHORD. If LRCHD = 0, then NCHORD evenly distributed chordwise divisions for the root is used. (Integer ≥ 0) (See Remark 2)
ATTCHR	Wing-body attachment condition for the wing root; = 0 no attachment, > 0 ID number of **BODY7** bulk data card to which the wing component is attached (Integer ≥ 0) (Default = 0)(See Remark 5)
XTL YTL ZTL	X, Y, and Z location of the tip chord leading edge (Real)
TCH	Length of the tip chord (Real)
LTCHD	Identification number of **AEFACT** bulk data card used to specify the tip chord divisions of the wing component in percentage of the tip chord. The number of values listed in **AEFACT** must be NCHORD. If LTCHD = 0, then evenly distributed chordwise divisions for the tip is used. (Integer ≥ 0) (See Remark 2)
ATTCHT	Wing-body attachment condition for the wing tip; = 0 no attachment, > 0 ID number of **BODY7** bulk data card to which the wing component is attached (Integer ≥ 0) (Default = 0)(See Remark 5)

Remarks:

1. All coordinate locations defined above in XRL, YRL, ZRL, XTL, YTL, and ZTL are in the local wing coordinate system defined by the **ACOORD** bulk data card.

2. The values listed in these **AEFACT** cards referenced by LSPAN, LRCHD and LTCHD must start with 0.0 and end with 100.0.

3. The number of spanwise and chordwise divisions of the wing component includes the end points; therefore, there will be NSPAN-1 spanwise strips, NCHORD-1 chordwise strips, NSPAN × NCHORD aerodynamic grids and (NSPAN-1) × (NCHORD-1) aerodynamic boxes generated by each **CAERO7** bulk data card. Among all aerodynamic grids and boxes, respectively, (of the **CAERO7** and **BODY7** bulk data cards) no duplicate identification number is allowed. The following figure demonstrates the numbering scheme.

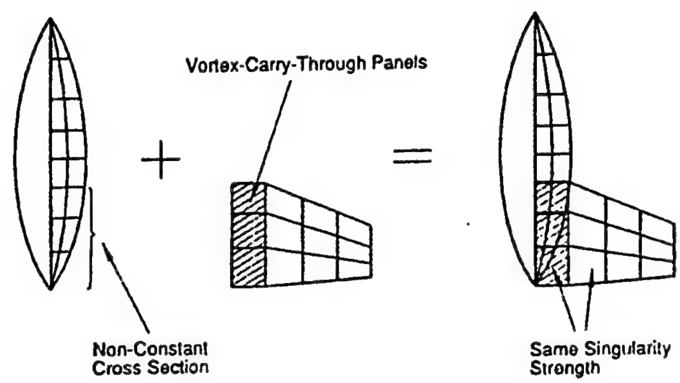


In the example given above, a **CAERO7** has WID=101, NSPAN=5 and NCHORD=4. There will be (5-1) x (4-1) = 12 aero boxes and 5 x 4 = 20 aero grid points generated for this lifting surface. Wing boxes are numbered starting with the wing id of 101 and ending at 112. Wing aero grid points are numbered starting with the wing id of 101 and ending at 120. A duplicate identification number (i.e. aero box(es) and aero grid point(s)) would occur, for example, if another lifting surface were defined with a wing id of say 112, since there would be two aero boxes with id's of 112 and duplicate aero grids of 112, 113, etc. Therefore, for this case, the next closest wing id (WID) or body id (BID) that could be used is 121.

4. The identification numbers of the aerodynamic grids and boxes are numbered sequentially beginning with WID.

5. The ATTCHR and ATTCHT entries define the condition whereby a wing root and tip, respectively, are attached to their associated bodies. Failure to attach the wing to its associated body will result in the wing aerodynamics being computed for a "free edge" at this wing-body junction. A value of zero implies that there is <u>no</u> attachment to a body.

   Typical wing-body paneling generates a spurious vortex line emanating from the wing-body junction. To circumvent this problem, the ATTCHR/ATTCHT option is provided and should be used for all wing-body junctions. For bodies with non-constant cross section within the wing-body junction the program will generate (NCHORD-1) number of "vortex-carry-through" (VCT) aero boxes inside the body between the wing root and the body center line. These VCT aero boxes are flat and their singularity strengths are set to be equal to their adjacent wing-root aero boxes. In this way, the left hand side and right hand side VCT aero boxes carry the line vortex from the wing root through the body and cancel it at the center of the body. In addition, the VCT aero boxes fill up any undesirable gaps between the wing root and body surface due to aero box modeling restrictions (see figure below). Since VCT aero boxes create no additional unknowns the total number of singularity strengths remains unchanged.



6. The <u>upper surface</u> of a **CAERO7** is defined by the normal vector which is computed by the cross product of the vector along the chord (leading edge to trailing edge) to the vector along the span (root to tip).

Input Data Card: **CHORDCP** ZONA Chordwise Steady Pressure Input

Description: Defines the upper and lower surface chordwise steady pressure at a strip; referenced by the **MACHCP** bulk data card.

Format and Example:

1	2	3	4	5	6	7	8	9	10
CHORDCP	ID	X1	CPU1	CPL1	X2	CPU2	CPL2		CONT
CONT		X3	CPU3	CPL3	X4	CPU4	CPL4	-etc-	

CHORDCP	10	0.0	-1.0	0.3	10.0	0.5	0.2		ABC
+BC		50.0	0.2	0.1					

Field	Contents
ID	**CHORDCP** identification number (Integer > 0)
Xi	X location of the CPUi and CPLi in percentage of the chord length. Xi must be in ascending order (i.e. Xi+1 > Xi). (Real)
CPUi	Steady pressure coefficient on the upper surface (Real)
CPLi	Steady pressure coefficient on the lower surface (Real)

Remarks:

1. The steady pressure coefficient can be provided either by steady Computational Fluid Dynamics (CFD) codes or wind tunnel measurement. It is recommended that the viscous effects be included in the steady CFD computations.

2. The first X location should be less than 1% and the last X location should be greater than 99.7%. Failure in meeting these two conditions will result in poor extrapolation of the steady pressure at the leading and trailing edges.

Input Data Card: **FLUTTER** ZONA Aerodynamic Flutter Data

Description: Defines data needed to perform flutter analysis.

Format and Example:

1	2	3	4	5	6	7	8	9	10
FLUTTER	SETID	METHOD	DENS	IDMK	VEL	MLIST	KLIST	EFFID	CONT
CONT	SYMXZ	SYMXY	EPS	CURVFIT	PRINT				

FLUTTER	100	PKK	1		3	4			ABC
+BC	-1	1000			1				

Field	Contents
SETID	Unique set identification number (Integer > 0) (See Remark 1)
METHOD	Flutter analysis method, 'PK' for PK-method, 'K' for K-method, and 'PKK' for both PK and K method. K-method is not used for optimization.
DENS	Identification number of an **FLFACT** bulk data card specifying density ratios to be used in flutter analysis (Integer > 0) (See Remark 2)
IDMK	Identification number of an **MKAEROZ** bulk data card (Integer > 0) (See Remark 3)
VEL	Identification number of an **FLFACT** bulk data card specifying velocities to be used in the flutter analysis (Integer > 0)
MLIST	Identification number of a **SET1** bulk data card specifying a list of normal modes to be OMITTED from the flutter analysis (Integer ≥ 0, or blank) (See Remark 4)
KLIST	NOT USED
EFFID	Identification number of a **CONEFFF** bulk data card specifying control surface effectiveness values (Integer ≥ 0, or blank) (See Remark 5)
SYMXZ	Symmetry flags associated with the aerodynamics (Integer) (See Remark 6) +1 Symmetric 0 or blank Asymmetric -1 Antisymmetric
SYMXY	NOT USED
EPS	Convergence parameter for flutter eigenvalue (Real > 0.0, default = 0.00001)
CURVFIT	Type of curve fit to be used in the PK-method. One of LINEAR, QUAD, CUBIC, or ORIG (Text, Default = 'LINEAR') (See Remark 7)

PRINT Print Flag (Integer ≥ 0).
PRINT=0, No print.
PRINT=1, Print out the generalized aerodynamic forces.
PRINT=2, Print out unsteady pressures and generalized aerodynamic forces.
PRINT=3, Print out unsteady pressures, generalized aerodynamic forces, and modes shapes on aerodynamic boxes (K-set).
For Optimization, PRINT ≠ 0 will result print-out at every iteration step.

Remarks

1. To perform the flutter analysis discipline, the FLUTTER discipline must be selected in the Solution Control packet with FLCOND=SETID.

2 The density used in the flutter analysis are given by RHOREF (defined by the **AEROZ** bulk data card) times the density ratio(s) listed in **FLFACT** bulk data card.

3. Mach number, reduced frequencies and mean flow condition used in the flutter analysis are those listed in the **MKAEROZ** bulk data card with identification number IDMK.

4 If the MLIST is blank or zero, all computed normal modes will be retained in the flutter analysis.

5 If EFFID is blank or zero, no control surface effectiveness corrections will be made.

6. The symmetry flags are to be used to select the appropriate aerodynamic matrices generated by the **MKAEROZ** bulk data card.

7. The LINEAR, QUAD, and CUBIC fits are separated first, second, and third order, respectively, fits of the real and imaginary terms of the generalized aerodynamic matrices at each reduced frequency.

Input Data Card: **GUST** ZONA Aerodynamic Gust Data

Description: Defines data needed to perform gust analysis.

Format and Example:

1	2	3	4	5	6	7	8	9	10
GUST	SETID	GLOAD	WG	XO	V	QDP	IDMK		CONT
CONT	SYMXZ								

GUST	100	10	1.0	0.0	1.E+4	13.5	.9	100	ABC
+BC	-1								

Field	Contents
SETID	Unique set identification number (Integer > 0) (See Remark 1)
GLOAD	The SID of a **TLOAD** or **RLOAD** bulk data card which define the time or frequency dependence (Integer > 0)
WG	Scale factor (gust velocity/forward velocity) for gust velocity (Real > 0.0)
XO	Loaction of the reference plane in the aerodynamic coordinates (Real)
V	Velocity of vehicle (Real > 0.0)
QDP	Dynamic pressure (Real > 0.0)
IDMK	Identification number of **MKAEROZ** bulk data card (Integer > 0) (See Remark 1)
SYMXZ	Symmetry flags associated with the aerodynamics (Integer) (See Remark 2) +1 Symmetric 0 or blank Asymmetric -1 Antisymmetric

Remarks

1. Mach number, reduced frequencies used in the gust analysis are those listed in the **MKAEROZ** bulk data card with identification number IDMK.

2. The symmetry flags are to be used to select the appropriate aerodynamic matrices generated by the **MKAEROZ** bulk data card. Also, if SYMXZ=1 or 0, the vertical (i.e. positive Z) gust is assumed. If SYMXZ=-1, the lateral (i.e. positive Y) gust is assumed.

Input Data Card: **LOADMOD** ZONA Load Modes Generater

Description: Defines the load mode of a set of structural grid points for computing component loads.

Format and Example:

1	2	3	4	5	6	7	8	9	10
LOADMOD	LID	LABEL	CP	SETK	SETG				

LOADMOD	10	XSHEAR	1	1					

Field	Contents
LID	**LOADMOD** identification number (Integer > 0)
LABEL	Type of loads defined by the load mode (Character) Must be one of the following: **XSHEAR** Shear force along X-axis of the coordinate system CP. **YSHEAR** Shear force along Y-axis of the coordinate system CP. **ZSHEAR** Shear force along Z-axis of the coordinate system CP. **XMOMENT** Bending moment about X-axis of the coordinate system CP. **YMOMENT** Bending moment about Y-axis of the coordinate system CP. **ZMOMENT** Bending moment about Z-axis of the coordinate system CP.
CP	Identification number of a rectagular coordinate system (Integer ≥ 0)
SETK	Identification number of a **PANLST1** or **PANLST2** bulk data card used to define the aerodynamic box id's (Integer > 0)
SETG	Identification number of **SET1** bulk data card used to define the structural grid points (Integer>0)

Remarks:

1. The forces at the structural grid points of SETK and SETG are integrated for structural loads and aerodynamic loads, respectivly, according to type of the loads defined by LABEL.

2. If CP=0, the basic coordinate system is used.

Input Data Card: **MACHCP** ZONA Mach Number and Steady Pressure Relation

Description: Establishes the correlation between the steady pressure for given spanwise stations with Mach number; referenced by the **ZTAIC** bulk data card.

Format and Example:

1	2	3	4	5	6	7	8	9	10
MACHCP	ID	MACH	IGRID	INDICA	SPANID	CHDCP	SPANID	CHDCP	CONT
CONT	SPANID	CHDCP	-etc-						

MACHCP	10	0.9	1	1	2	12	3	9	ABC
+BC	4	10	5	15	6	17			

Field	Contents
ID	**MACHCP** identification number (Integer > 0)
MACH	Mach number (Real)
IGRID	Index of grid mesh; |IGRID| = 0 or 1 employs a standard grid mesh, = 2 employs a fine grid mesh, = 3 employs a fine grid mesh and doubles the number of time steps. Also, if IGRID ≥ 0, chordwise bending effects are included, whereas, if IGRID < 0 chordwise bending effects are not included. (Integer)
INDICA	Index for type of motion for the transformation from time domain solution to frequency domain; = 0 sinusoidal motion is employed, = 1 indicial motion is employed (Integer)
SPANIDi	Spanwise strip index corresponding to the spanwise location of the chordwise steady C_P distribution of CHDCPi entry. The spanwise location is at the center of the strip. Each **CAERO7** bulk data card has (NSPAN-1) number of spanwise strips. The indicies of the strips, therefore, vary from 1 to (NSPAN-1). Note that 0 < SPANIDi < NSPAN. (Integer > 0)
CHDCPi	Identification number of the **CHORDCP** bulk data card (Integer > 0)

Remarks:

1. The flow-field grid system used by the ZTAIC method in solving the unsteady transonic small disturbance equation is fixed in that only two grid systems (or meshes) can be selected. In addition, only two (2) options are allowed for a given number of time steps in the computation (i.e. the standard time step and the doubled time step).

2. Using the fine grid mesh (i.e. |NGRID| = 2) will increase the CPU computing time by approximately twenty-five percent.

3. Including the chordwise bending effects will result in an increase of CPU computing time of approximately twenty percent. However, it is recommended to include the chordwise bending effects unless the wing structure is modeled as a beam.

4. The number of SPANIDi and CHDCDi pairs should be NSPAN-1, where SPANIDi starts with 1 and ends with NSPAN-1. Among all strips defined, the absence of a SPANIDi will result in no steady pressure input at this

particular strip. In this case, the unsteady pressure distribution at this particular strip will be computed by the linear method.

Input Data Card: **MKAEROZ** ZONA Mach Number - Reduced Frequency - Flight Conditions

Description: Define Mach number, mean flow conditions, and list of reduced frequencies for steady/unsteady aerodynamic data generation.

Format and Example:

1	2	3	4	5	6	7	8	9	10
MKAEROZ	IDMK	MACH	METHOD	IDFLT	SAVE	FILENM		PRINT	CONT
CONT	FREQ1	FREQ2	FREQ3	FREQ4	etc.				

MKAEROZ	100	0.9	1	2.0	SAVE	ZAERODATA		-3	ABC
+BC	0.001	0.1	0.3	2.0					

Field	Contents
IDMK	Unique identification number (Integer > 0) (See remark 1)
MACH	Mach number (Real ≥ 0.0) (See Remark 2)
METHOD	Flag for specifying linear or nonlinear aerodynamic methods (Integer ≥ 0, or blank) (See Remark 3)
IDFLT	Identification number of **TRIMFLT** bulk data card (Integer ≥ 0) (See Remark 4)
SAVE	Save or retrieve the Aerodynamic Influence Coefficient (AIC) data generated by the current **MKAEROZ** bulk data card from file 'FILENM.IDMK' (Characters or blank) SAVE= SAVE saves the AIC data. SAVE= ACQUIRE retrieves an existing file containing AIC data. Otherwise do not save or retrieve data.
FILENM	File name (up to 16 characters) to spciefy the file name on which the AIC data is saved or retrieved (Character or blank).(See Remark 5)
PRINT	Print flag (Integer) PRINT= 0 No print. PRINT= ±1 Print out the aerodynamic pressure coefficients and stability derivatives of the rigid body motions (Forward-Aftward translation, plunge, and pitch motions for symmetric case; Lateral translation, roll, and yaw motions for antisymmetric case). PRINT= ±2 Print out the aerodynamic pressure coefficients and stability derivatives of the control surface motion and load modes (For all **AESURFZ** and **LOADMOD** bulk data cards). PRINT< 0 Print out the aerodynamic geometric data.
FREQi	Reduced frequencies (Real > 0.0) (See Remark 6)

Remarks

1. All **MKAEROZ** bulk data cards will be processed by the ZAERO module for the generation of unsteady/steady aerodynamic data in the preface module regardless wether they are or are not used by **FLUTTER**, **GUST**, and **TRIM** bulk cards. If XZSYM = 'YES' in the **AEROZ** bulk data card, both symmetric and anti-symmetric data will be computed. IDMK is referred by the **FLUTTER**, **GUST**, and **TRIM** bulk data cards. For **TRIM**, the steady aerodynamic data is retrieved from the real part of the unsteady aerodynamic data of the lowest reduced frequency (The lowest reduced frequency is hotwired to be 0.001, See Remark 6).

2. Each **MKAEROZ** specifies only one Mach number.

3. If :
   METHOD = 0 and MACH < 1.0, the ZONA6 method is used.
   METHOD = 0 and MACH > 1.0, the ZONA7 method is used.
   METHOD = 1 and MACH < 1.0, the ZTAIC method is used.
   METHOD = 1 and MACH > 1.0, the ZONA7U method is used.

   When the ZTAIC method is selected, the bulk data card **ZTAIC** must exist. The Mach number (MACH) must be exactly the same as one of the Mach numbers specified in the bulk data cards **MACHCP**. Interpolation of steady pressure coefficients among Mach numbers of those listed in the **MACHCP** bulk data cards is not allowed.

   When the ZONA7U method is selected, the supersonic thickness effect is included. The thickness distributions of the **CAERO7** cards are computed based on the airfoil sections specified in the **PAFOIL7** bulk data cards.

4. The **TRIMFLT** bulk data card defines the mean flow condition. The unsteady aerodynamic data is computed by the perturbation about the mean flow condition. This implies that the unsteady aerodynamics is coupled with the steady mean flow aerodynamics. If IDFLT=0, then zero mean flow is employed.

5. The actual name of the file is XXXXXX.iiii . Where XXXXXX=FILENM and iiii=IDMK.

6. Reduced frequency k is defined as:

$$k = \frac{\omega \left(\frac{REFC}{2}\right)}{V_\infty}$$

   where REFC is the reference chord length defined in the **AEROZ** bulk data card.

   Since the PK method used in the **FLUTTER** bulk data card requires the first reduced frequency to be a small but non-zero value, the value of the first reduced frequency is hotwired to be 0.001. Any values of RFREQi less than 0.001 will be ignored. If all values of RFREQi are larger than 0.001, one additional reduced frequency with a value of 0.001 will be added in the reduced frequency list.

Input Data Card: **PAFOIL7** ZONA Airfoil Section Property

Description: Defines the airfoil cross sections at the root and tip for the ZONA7U method; referenced by the **CAERO7** bulk data card.

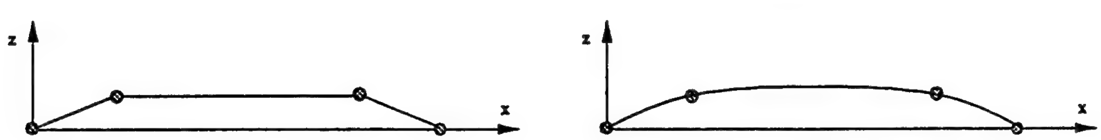
Format and Example:

1	2	3	4	5	6	7	8	9	10
PAFOIL7	ID	ITAX	ITHR	ICAMR	RADR	ITHT	ICAMT	RADT	
PAFOIL7	1	-201	202	203	0.1	211	212	0.1	

Field	Contents
ID	**PAFOIL7** identification number (Integer > 0)
ITAX	Identification number of an **AEFACT** bulk data card used to specify the X coordinate locations, in percentage of the chord length, where the thickness and camber are to be specified. ITAX can be a negative number (where ABS(ITAX) = **AEFACT** bulk data card identification number) to request linear interpolation (Integer) (See Remark 1)
ITHR	Identification number of an **AEFACT** bulk data card used to specify the half thickness of the airfoil at the wing root (Integer ≥ 0)
ICAMR	Identification number of an **AEFACT** bulk data card used to specify the camber of the airfoil at the wing root (Integer ≥ 0)
RADR	Leading edge radius at the root (Real ≥ 0.0)
ITHT	Identification number of an **AEFACT** bulk data card used to specify the thickness at the wing tip (Integer ≥ 0)
ICAMT	Identification number of an **AEFACT** bulk data card used to specify the camber at the wing tip (Integer ≥ 0)
RADT	Leading edge radius at the tip (Real ≥ 0.0)

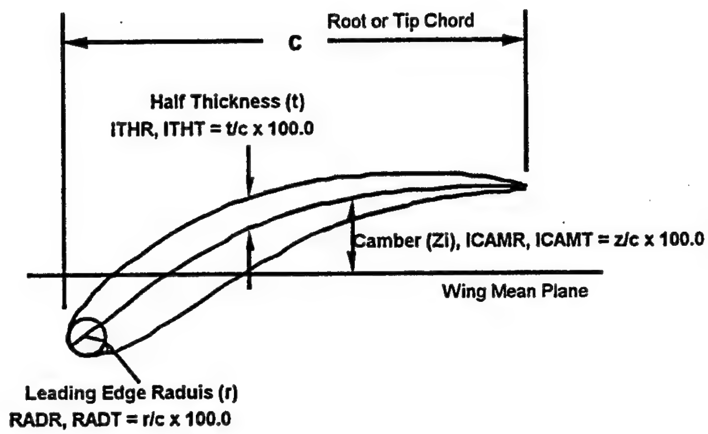
Remarks:

1. The ITAX X coordinate values listed in the **AEFACT** bulk data card must start with 0.0 and end with 100.0. If ITAX is a positive integer, then a cubic interpolation is used between the airfoil points established by the ITAX, ITHR, ICAMR, RADR, ICAMT and RADT entries. However, ITAX can be a negative number which implies that a linear interpolation is used between the airfoil points. For example, if the desired airfoil shape at the wing root is shown in (a) below, and a positive value for ITAX were used, the resulting airfoil shape would be that shown in (b) which is incorrect. In this case a negative value for ITAX is required to generate the airfoil shape shown in (a).



(a) (b)

2. ITH(R)/(T), ICAM(R)/(T) and RAD(R)/(T) values listed in the **AEFACT** bulk data cards are in percentage of the root/tip chord lengths (c), respectively. See following figure.



3. The number of values listed in the **AEFACT** cards for ITAX, ITHR, ICAMR, ITHT and ICAMT must be the same.

4. The camber and thickness distributions are computed by linear interpolation from the wing root to the wing tip.

Input Data Card: **PANLST1** ZONA Set of Aerodynamic Boxes

Description: Defines a set of aerodynamic boxes.

Format and Example:

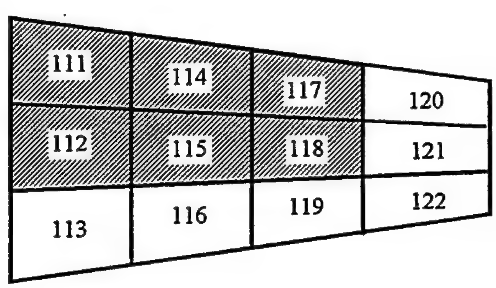
1	2	3	4	5	6	7	8	9	10
PANLST1	SETID	MACROID	BOX1	BOX2					

PANLST1	100	111	111	118					

Field	Contents
SETID	Unique set identification number (Integer > 0)
MACROID	Element identification number of a **CAERO7** bulk data card to which the aerodynamic boxes listed in the set belong (Integer > 0)
BOX1	Identification number of the first aerodynamic box (Integer > 0)
BOX2	Identification number of the last aerodynamic box (Integer > BOX1)

Remarks:

1. **PANLIST1** is referred to by a **SPLINEi** and/or **AESURFZ** bulk data card.
2. The following sketch shows the boxes identified via BOX1 and BOX2 entries, if BOX1 = 111, BOX2 = 118 and MACROID = 111



Input Data Card: **PANLST2** ZONA Set of Aerodynamic Boxes

Description: Defines a set of aerodynamic boxes.

Format and Example:

1	2	3	4	5	6	7	8	9	10
PANLST2	SETID	MACROID	BOX1	BOX2	BOX3	BOX4	BOX5	BOX6	CONT
CONT	BOX7	etc.							

PANLST2	100	101	101	THRU	200				

Field	Contents
SETID	Unique set identification number (Integer > 0)
MACROID	Element identification number of a **CAERO7** bulk data card to which the aerodynamic boxes listed in the set belong (Integer > 0)
BOXi	Identification number of aerodynamic boxes (Integer > 0)

Remarks:

1. **PANLST2** is referred by a **SPLINEi** and/or **AESURFZ** bulk data card.

Input Data Card: **PBODY7** ZONA Aerodynamic Body Wake/Inlet Property

Description: Defines the wake and inlet aero boxes of a aerodynamic body; referenced by the **BODY7** bulk data card.

Format and Example:

1	2	3	4	5	6	7	8	9	10
PBODY7	ID	WAKE	CPBASE	XSWAKE	XDWAKE	YOFF	ZOFF	INLET	CONT
CONT	IDP1	FLOWRT1	IDP2	FLOWRT2	-etc-				

PBODY7	2	1	-0.2	1.3	1.1	0.8	0.8	4	+ABC
+BC	101	0.0	103	100.					

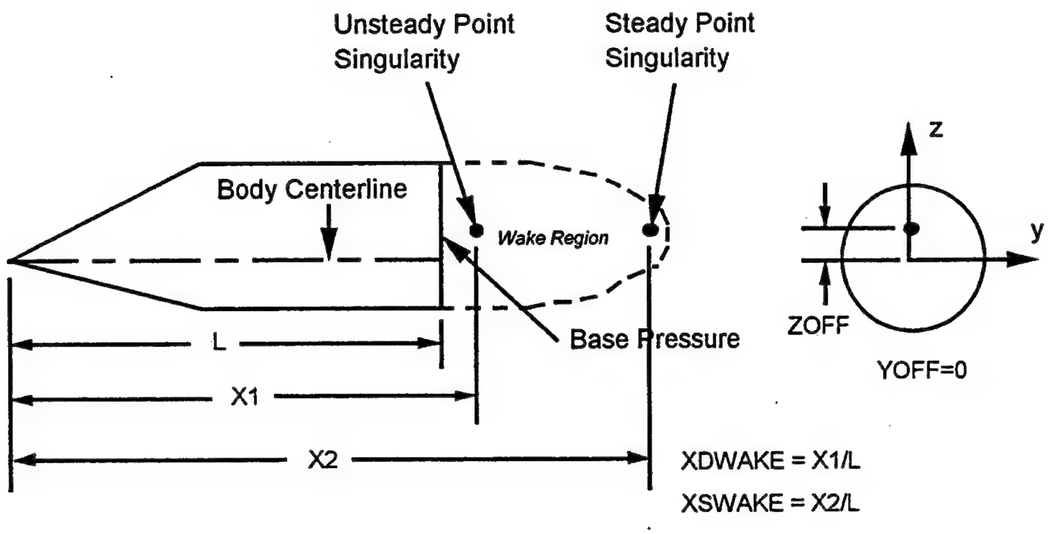
Field	Contents
ID	**PBODY7** identification number (Integer > 0)
WAKE	Body wake condition; = 1 with wake; = 0 no wake (Integer 0 or 1)
CPBASE	Steady base pressure coefficient (Real, Default = -0.2)
XSWAKE	X location of the steady point singularity in terms of a fraction of the body length as measured from the nose of the body (Real > 1.0, Default = 1.3)
XDWAKE	X location of the unsteady point singularity in terms of a fraction of the body length as measured from the nose of the body (Real > 1.0, Default = 1.1)
YOFF	Y offset from the body centerline used to define the steady and unsteady point singularity locations (Real ≥ 0, Default = 0)
ZOFF	Z offset from the body centerline used to define the steady and unsteady point singularity locations (Real ≥ 0, Default = 0)
INLET	Number of body inlet aero boxes (Integer ≥ 0)
IDPi	Body box identification numbers on which the flow is allowed to penetrate into the body; denoted as "inlet boxes" (Integer > 0)
FLOWRTi	Amount of flow in percentage of the flow contained in the stream tube in front of the inlet aero box which penetrates into to the body (Real)

Note: See Remarks on Next Page

Remarks:

1. All coordinate locations defined above in XSWAKE, XDWAKE, YOFF, and ZOFF are in the local body coordinate system defined by the **ACOORD** bulk data card.

2. The point singularities serve as additional unknowns whose strengths are determined by the steady base pressure coefficient. This body wake condition simulates the separated flow at the truncated end body as demonstrated in the following figure.



3. If WAKE= 0, CPBASE, XSWAKE, XDWAKE, YOFF and ZOFF are not required.

4. There must be INLET numbers of IDPi and FLOWRTi pairs (i.e. IDPi, FLOWRTi i=1, INLET). If no flowpenetrates in to the aero box, FLOWRT=0, whole flow penetrates in to the aero box, FLOWRT=100.

5. If the inclination angle of the aero box exceeds the Mach cone angle in supersonic flow (the Mach Cone angle can be computed by Arcsin(1.0/M), where M=free stream Mach number), then linear theory fails. This kind of aero box orientation is defined as Superinclined Box which normally occurs on the engine inlet face or the nose section of blunt bodies. To resolve this problem, any Superinclined Boxes can be specified as <u>inlet</u> aero boxes. Special treatment of the inlet aero boxes will be performed. For an inlet aero box located on the nose of the body, FLOWRT=0.0 is recommended. For an engine face, the vaule of FLOWRT should be defined based on the engine operating conditions.

Input Data Card: **SEGMESH** ZONA Body Segment Definition

Description: Defines a mesh grid system for a body segment; referenced by the **BODY7** bulk data card.

Format and Example:

1	2	3	4	5	6	7	8	9	10
SEGMESH	IDMESH	NAXIS	NRAD						CONT
CONT	ITYPE	X1	CAM1	YR1	ZR1	IDY1	IDZ1		CONT
CONT	ITYPE2	X2	CAM2	YR2	ZR2	IDY2	IDZ2		CONT
CONT	ITYPE2	X3	CAM3	YR3	ZR3	IDY3	IDZ3	-etc-	

SEGMESH	2	3	6						ABC
+BC	1	0.0	0.0	0.0					DEF
+EF	1	1.0	0.0	0.5					GHI
+HI	3	2.0				103	104		

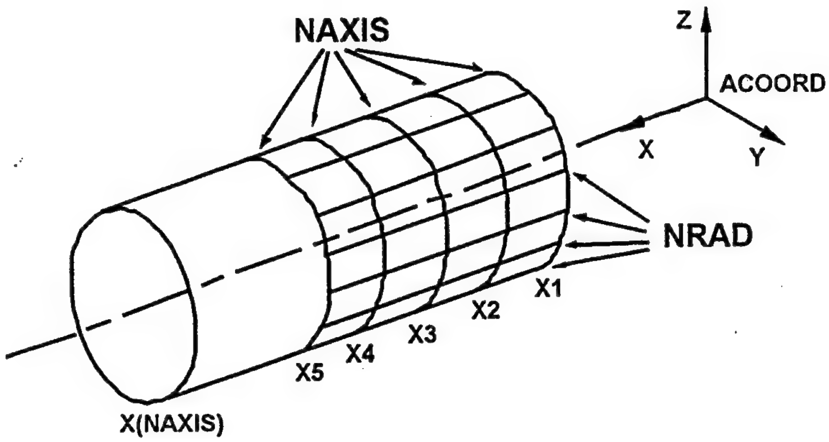
Field	Contents
IDMESH	Body segment mesh identification number (Integer > 0)
NAXIS	Number of axial stations (i.e. divisions) of the segment (Integer ≥ 2)
NRAD	Number of circumferential points of the segment (Integer ≥ 3)
ITYPEi	Type of input used to define the circumferential box cuts; = 1 body of revolution, = 2 elliptical body, = 3 arbitrary body (Integer 1, 2, or 3) (See Remark 3)
Xi	X location of the axial station; Xi must be in ascending order (i.e. Xi+1 > Xi) (Real)
CAMi	Body camber at the Xi axial station (Real)
YRi	Body cross-sectional radius if ITYPEi = 1 or the semi-axis length of the elliptical body parallel to the Y-axis if ITYPEi = 2 (Real)
ZRi	The semi-axis length of the elliptical body parallel to the Z-axis (Real)
IDYi	Identification number of **AEFACT** bulk data card that specifies NRAD number of the Y coordinate locations of the circumferential points at the Xi axial station (Integer > 0)
IDZi	Identification number of **AEFACT** card that specifies NRAD number of the Z coordinate locations of the circumferential points at the Xi axial station (Integer > 0)

Note: See Remarks on Next Page

Remarks:

1. All coordinates are in the local body coordinate system defined by the **ACOORD** bulk data card.

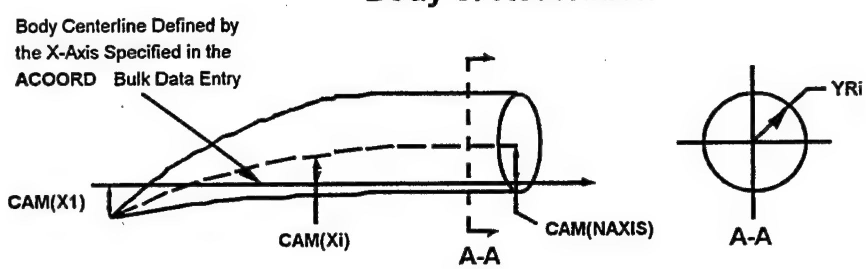
2. ITYPEi through IDZi entries must be repeated for each axial station of the body segment (i.e. NAXIS times), therefore, CAMi, YRi, ZRi, IDYi and IDZi represent the circumferential points at Xi.



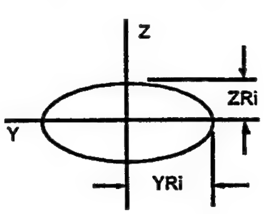
3. There are three methods to define the circumferential points at a given axial station:

   1) Body of Revolution (using ITYPEi = 1, and Xi, CAMi, YRi entries)
   2) Elliptical Body (using ITYPEi = 2, and Xi, YRi, ZRi entries)
   3) Arbitrary Body (using ITYPEi = 3, and Xi, IDYi, IDZi entries)

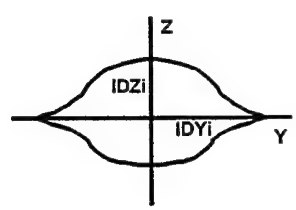
Body of Revolution



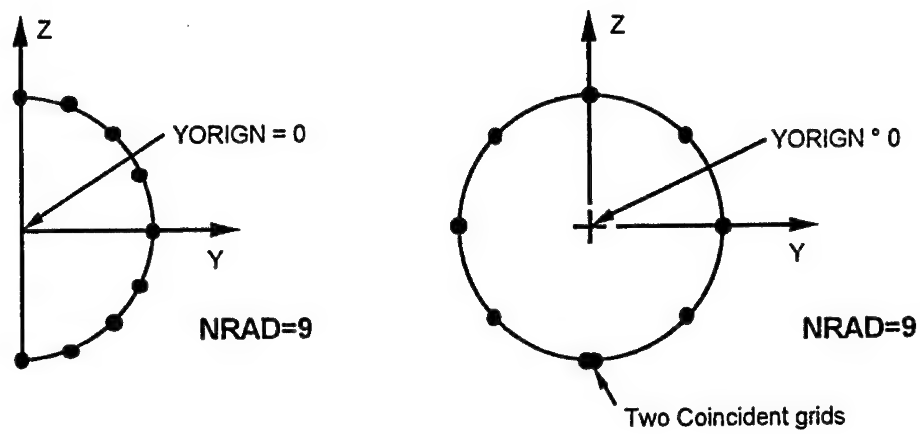
Elliptical Body



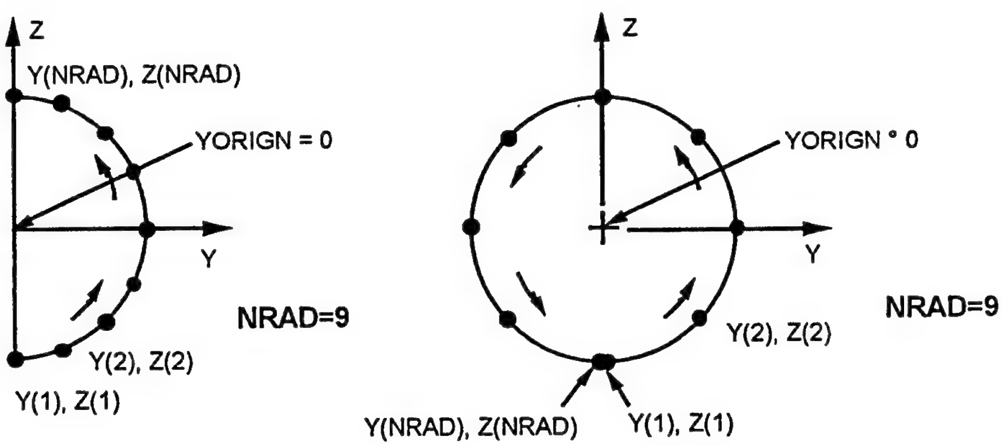
Arbitrary Body



For a <u>body of revolution</u> or <u>elliptical body</u>, the number of circumferential points are divided evenly for the body. If YORIGN defined in the **ACOORD** bulk data card to which the body refers is zero, only half of the body (on the positive Y side) is generated. Conversely, if YORIGN is not zero, the points must be distributed over the entire circumference of the body. For this case, the first and last points will be coincident points. (See figures below)



For an <u>arbitrary body</u>, the circumferential points must be entered in a counterclockwise fashion as viewed along the X-axis looking at the Y-Z plane (in local body coordinates). If YORIGN defined in the **ACOORD** bulk data card to which the body refers is zero, only half of the body (on the positive Y side) is generated. Conversely, if YORIGN is not zero, the points input must be distributed over the entire circumference of the body. For both of these cases, the Y values listed in the **AEFACT** bulk data card must start with zero and end with zero. (See figure below)



4. The number of aerodynamic grids and boxes generated by each segment is NAXIS × NRAD and (NAXIS-1)× (NRAD-1); therefore, there are $\sum_{i=1}^{NSEG} NAXIS_i \times NRAD_i$ and $\sum_{i=1}^{NSEG} (NAXIS_i - 1) \times (NRAD_i - 1)$ number of grids and boxes, respectively, for each **BODY7** bulk data card.

Input Data Card: **SPLINE1** ZONA Surface Spline Method

Description: Defines a infinite plate spline method for displacements and loads transformation between aerodynamic and structural models.

Format and Example:

1	2	3	4	5	6	7	8	9	10
SPLINE1	EID	MODEL	CP	SETK	SETG	DZ	EPS		

SPLINE1	100			20	30	0.0			

Field	Contents
EID	Unique element identification number (Integer > 0) (See Remark 1)
MODEL	NOT USED
CP	Coordinate system defining the spline plane (Integer ≥ 0 or blank) (See Remark 2)
SETK	Refers to a **PANLST1** or **PANLST2** bulk data card that lists the aerodynamic box identification numbers (Integer > 0)
SETG	The identification of a **SETi** bulk data card that lists the structural grid points to which the spline is attached (Integer > 0)
DZ	Linear attachment flexibility (Real ≥ 0.0)
EPS	Small tolerance to detect any duplicated location of structural points (Real ≥ 0.0, Default = 0.01). (See Remark 3)

Remarks:

1. EID is only used for error output.
2. If no CP is specified, the plane defined by the macroelement specified in the **PANLSTi** bulk data card is used for the spline plane.
3. If any two or more structural point locations projected on the spline plane are nearly the same, the spline matrix will be singular. EPS is used to detect this condition.

Input Data Card: **SPLINE2** ZONA Beam Spline Method

Description: Defines a beam spline method for the **BODY7** or **CAERO7** macroelement.

Format and Example:

1	2	3	4	5	6	7	8	9	10
SPLINE2	EID	MODEL	SETK	SETG	DZ	DTOR	CID	DTHX	CONT
CONT	DTHY								

SPLINE2	100		10	20	0.0	0.0			

Field	Contents
EID	Unique element identification number (Integer > 0) (See Remark 1)
MODEL	NOT USED
SETK	Refers to a **PANLST1** or **PANLST2** bulk data card that lists the aerodynamic box identification numbers (Integer > 0)
SETG	The identification of a **SETi** bulk data card that lists the structural grid points to which the spline is attached (Integer > 0)
DZ	Linear attachment flexibility (Real ≥ 0.0)
DTOR	Torsional flexibility, EI / GJ (Real ≥ 0.0, use 1.0 for **BODY7**)
CID	Rectangular coordinate system that defines the Y-axis of the spline (Integer ≥ 0 or blank; not used for **BODY7**) (See Remark 2)
DTHX, DTHY	Rotational attachment flexibility. DTHX is for rotation about the X-axis; not used for bodies. DTHY is for rotation about the Y-axis; used for slope of bodies. (Real)

Remarks:

1. EID is only used for error output.

2. If the macroelement specified in the **PANLSTi** bulk data card is a **CAERO7**, the spline axis is the Y-axis of the coordinate system CID. If it is a **BODY7**, the flow direction is defined by the **AEROZ** bulk data card.

3. The flexibilities are used for smoothing. Zero attachment flexibilities will imply rigid attachment, (i.e. no smoothing). Negative values of DTHX and/or DTHY will imply no attachment.

4. The continuation card is optional.

Input Data Card: **SPLINE3** ZONA 3D Spline Method

Description: Defines a 3-D spline for the **BODY7** and **CAERO7** macroelement.

Format and Example:

1	2	3	4	5	6	7	8	9	10
SPLINE3	EID	MODEL	CP	SETK	SETG	DZ	EPS		

SPLINE3	100			1	10	0.0			

Field	Contents
EID	Unique element identification number (Integer > 0)
MODEL	NOT USED
CP	NOT USED
SETK	Refers to a **PANLST1** or **PANLST2** bulk data card that lists the aerodynamic box identification numbers (Integer > 0)
SETG	Refers to a **SETi** bulk data card that lists the structural grid points to which the spline is attached (Integer > 0)
DZ	NOT USED
EPS	Small tolerance to detect any duplicated structural point locations and any planar locations of all structural points (Real ≥ 0.0, Default = 0.01)

Remarks:

1. **SPLINE3** employs the thin plate spline (TPS) method. Unlike the surface spline method employed by the **SPLINE1** bulk data card, the **SPLINE3** does not require that a spline plane be defined. All structural grid points are located in 3-D space.

2. Two restrictions are associated with the spline method:

   (a) Similar to **SPLINE1**, no two or more structural points can be at the same location.

   (b) All of the structural points cannot be located in the same plane.

   EPS is the tolerance used to detect the above two conditions.

Input Data Card: **TRIM** ZONA Trim Variable Specification

Description: Specifies conditions for steady aeroelastic trim analysis and computes the associated aerodynamic data.

Format and Example:

1	2	3	4	5	6	7	8	9	10
TRIM	TRIMID	IDMK	QDP	TRMTYP	EFFID	VO	PRINT		CONT
CONT	LABEl1	VAL1	LABEL2	VAL2	LABEL3	VAL3	LABEL4	VAL4	-etc-

TRIM	1	0.9	13.5	LIFT	30	263.0	-1		ABC
+BC	NZ	9.0	QRATE	.243	ELEV	FREE	ALPHA	FREE	

Field	Contents
TRIMID	Trim set identification number (Integer > 0)
IDMK	Identification number of the **MKAEROZ** bulk data card (See Remark 2). (Integer > 0)
QDP	Dynamic pressure (Real > 0.0).
TRMTYP	Type of trim required (Character or blank) BLANK SUPORT controlled trim. ROLL Axisymmetric roll trim (1 DOF). LIFT Symmetric trim of lift forces (1 DOF). PITCH Symmetric trim of lift and pitching moment (2 DOF).
EFFID	Identification number of **CONEFFS** bulk data cards which modify control surface effectiveness values (Integer ≥ 0 or blank)
VO	True velocity (Real > 0.0)
PRINT	Print flag (Integer) PRINT= 0 No print. PRINT= ±1 Print out the aerodynamic pressure coefficients and stability derivatives associated all entries in the relation **STABCF**. PRINT= ±2 Print out the aerodynamic pressure coefficients and stability derivatives of the rigid body modes.
LABELi	Label defining aerodynamic trim parameters.
VALi	Magnitude of the specified trim parameter (Real) or the character string 'FREE'.

Remarks:

1. The **TRIM** card is selected in Solution Control in the SAERO disciplines with the **TRIM** option.

2. The definition of the input parameters is identical to that of the original **TRIM** bulk data card of ASTROS except the entry IDMK:

   (a) The steady aerodynamic data is computed based on the flight condition specified in the **MKAEROZ** bulk data card with idenfication number= IDMK.

   (b) The mean flow conditions defined by IDFLT of the **MKAEROZ** bulk data card can generate nonlinear aerodynamics. Trim analysis with non-zero mean flow conditions represents a small perturbation of the trim parameters about thier mean positions defined in the **TRIMFLT** bulk data card with ID=IDFLT.

Input Data Card: **TRIMFLT** ZONA Mean Flow Condition Specification.

Description: Specifies the mean flow conditions of steady and unsteady aerodynamics.

Format and Example:

1	2	3	4	5	6	7	8	9	10
TRIMFLT	IDFLT	TILTA	ALPHA	BETA	PRATE	QRATE	RRATE		CONT
CONT	LABEl1	VAL1	LABEL2	VAL2	LABEL3	VAL3	LABEL4	VAL4	-etc-

TRIMFLT	1		13.5	0.0	0.0	0.0	0.0		ABC
+BC	ELEV	9.0	RUDDER	3.0					

Field	Contents
IDFLT	**TRIMFLT** set identification number (Integer > 0)
TILTA	NOT USED
ALPHA	Angle of attack in degrees (Real)
BETA	Side slip angle in degrees (Real)
PRATE, QRATE, RRATE	Nondimensional Roll, Pitch, and Yaw rates (Real)
LABELi	Label of the control surfaces defined in the **AESURFZ** bulk data card (Character)
VALi	Control surfaces deflection angle in degrees (Real)

Remarks:

1. The **TRIMFLT** bulk data card can be referred to by:

    (a) **MKAEROZ** bulk data cards for unsteady aerodynamic data generation.

    In this case, ALPHA, BETA, PRATE, QRATE, RRATE and control surface deflections define the mean flow conditions. The unsteady aerodynamic data is computed by the perturbation about the mean flow conditions. This implies that the unsteady aerodynamics is coupled with the steady mean flow aerodynamics.

    (b) **TRIM** bulk data card for steady aerodynamic data generation.

    In this case, the trim analysis is performed with nonlinear aerodynamics and small perturbations about the mean values of ALPHA, BETA, PRATE, QRATE, RRATE, and control surface deflections.

2. LABEL must be defined in the **AESURFZ** bulk data cards.

3. The nondimensional roll, pitch, and yaw rates are defined as :

PRATE =	(roll rate)	*	(REFB/2.0) / V
QRATE =	(pitch rate)	*	(REFC/2.0) / V
RRATE =	(yaw rate)	*	(REFB/2.0) / V

where V is the free stream velocity, REFB and REFC are the reference span and reference chord, respectively, specified in the **AEROZ** bulk data card.

Input Data Card: **ZTAIC** ZONA ZTAIC Method Steady Pressure Definition

Description: Defines bulk data cards to be used for sectional steady pressure input that is required by the ZTAIC (i.e. transonic aerodynamics) method; referenced by the **CAERO7** bulk data card.

Format and Example:

1	2	3	4	5	6	7	8	9	10
ZTAIC	ID	NFLAP	MACHCP	MACHCP	MACHCP	MACHCP	MACHCP	MACHCP	CONT
CONT	LABEl1	HINGE1	INBDY1	OUTBDY1	LABEL2	HINGE2	INBDY2	OUTBDY2	-etc-

ZTAIC	1	1	10	20	30				ABC
+BC	TE	8	1	5					

Field	Contents
ID	**ZTAIC** identification number (Integer > 0)
NFLAP	Number of control surfaces on the associated **CAERO7** bulk data card (Integer ≥ 0 or blank, Default = 0)
MACHCPi	Identification number of **MACHCP** bulk data (used to specify chordwise steady pressure distribution for a given Mach number and various spanwise locations) card (Integer > 0 or blank, Default = 0) (See Remark 1)
LABEli	Label of control surface. Must be either TE (trailing edge control surface) or LE (leading edge control surface). (Character)
HINGEi	Index of the chordwise division of the associated **CAERO7** bulk data card; represents the hinge line where the structural discontinuity occurs. Must be in the range of 1 < HINGEi < NCHORD. (Integer ≥ 1)
INBDYi	Index of the spanwise division of the associated **CAERO7** bulk data card; represents the inboard edge of the control surface (Integer ≥ 1)
OUTBDYi	Same as INBDYi, but for the outboard edge of the control surface (Integer)

Remarks:

1. The maximum number of **MACHCP** allowed is six (6).

2. Each **MACHCP** defines the steady pressure distribution over the wing at a given Mach number.

3. Among all **ZTAIC** bulk data cards, the total number of Mach numbers cannot exceed six (6). Incompatible Mach numbers on different **ZTAIC** bulk data cards is not recommended.

4. The term "control surface" represents a region on the **CAERO7** wing component where a structural discontinuity may occur due to a control surface. This type of control surface is used only if the ZTAIC method is selected for transonic unsteady aerodynamics.

5. The chordwise divisions (HINGEi) and spanwise divisions (INBDYi and OUTBDYi) must be aligned with the boundary of the control surface. In addition, the following must hold NSPAN ≥ OUTBDYi > INBDYi ≥ 1

5.0 MODELING GUIDELINES

This section presents some important aspects of ZAERO modeling and is intended to cover information that has not yet been covered in previous sections. The ZAERO module has been developed with as many checks as possible to detect any errors within the bulk data input. However, there are certain situations whereby incorrect modeling is not detectable by the program and may lead to incorrect results. Some of these situations can be avoided by following the modeling guidelines presented in this section.

5.1 Coordinate Systems of ZAERO and Structural Finite Element Models

Aeroelastic analysis involves the coupling of the aerodynamics and structural responses. In practice, the aerodynamic model and structural finite element model are constructed by different groups of engineers. This can result in a situation where the aerodynamic model and the structural finite element model are located in different regions within the same coordinate system. In order to transfer the displacements and loads between these two models, the spline module of ZAERO requires a coordinate transformation to align the overall geometries of the aerodynamic and structural models. This is discussed in the following sub-sections.

5.1.1 Aerodynamic Coordinates

The aerodynamic coordinate system is the coordinate system in which the ZAERO model geometry is defined. Since ZAERO solves the small disturbance potential equation, which inherently defines the x-axis as the compressible direction of the flow, the x-axis of the aerodynamic coordinates must be parallel to the flow direction (Fig 5.1). If a pilot were situated in a ZAERO model, the y-axis of the aerodynamic coordinates must be in the direction of the pilots right hand side (see Fig 5.1). If the aircraft configuration is symmetric about the x-z plane of the aerodynamic coordinates, ZAERO only requires modeling of half of the configuration. This is done by setting XZSYM='YES' in the **AEROZ** bulk data card. Again, the ZAERO model must be located on the right hand side of the pilot (i.e. the positive y-axis direction). In addition, the ZAERO model must be located at the zero angle-of-attack and zero side-slip angle conditions. The angle-of-attack and side-slip angle effects are introduced through the boundary conditions.

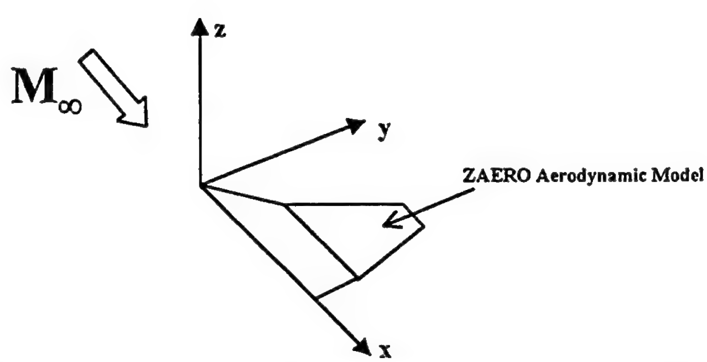


Figure 5.1 Proper Orientation of a ZAERO Model in the Aerodynamic Coordinate System.

5.1.2 Finite Element Model (FEM) Coordinates

Since the structural finite element model can be oriented in an arbitrary fashion with respect to the aerodynamic coordinates, a coordinate transformation to align the overall geometry of the ZAERO model with the finite element model is required. The FEM coordinates are a user-defined local coordinate system (with respect to the aerodynamic coordinates) whose axes are denoted here as x', y' and z'.

If a pilot were situated in the finite element model, the x'-axis would be toward the pilots face and the positive y'-axis would be on the pilot's right-hand-side. The FEM coordinates must be a rectangular coordinate system specified by either a **CORD1R** or **CORD2R** bulk data card. The identification number of the **CORD1R / CORD2R** is then referred to by ACSID of the **AEROZ** bulk data card. A negative ACSID can be specified. This indicates that the finite element model of the half aircraft is located on the left-hand-side of the pilot (i.e. in the negative y'-axis direction).

Fig 5.2 shows a finite element model of a half aircraft configuration whose fuselage is oriented along the negative y-axis of the aerodynamic coordinates and whose wing is parallel to the negative x-axis.

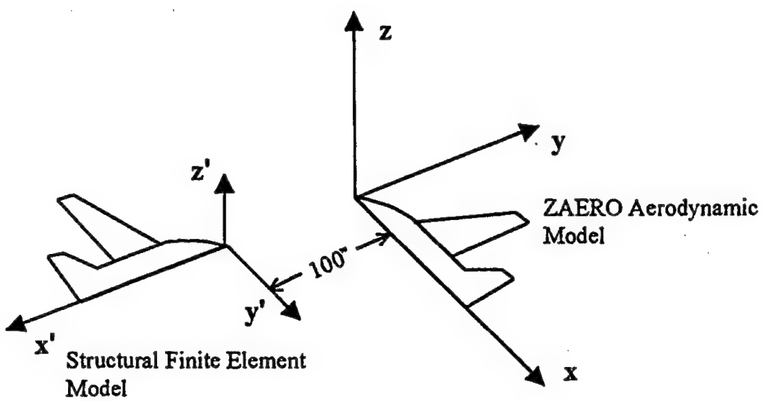


Figure 5.2 Definition of the Local Coordinates to Align the Finite Element and ZAERO Model Geometry.

It can be seen that the half finite element model is located on the pilots left-hand-side. The x', y' and z' coordinate system shown in Fig 5.2 represents the FEM coordinates and can be specified by a **CORD1R** or **CORD2R** bulk data card. As an example, the following **CORD2R** bulk data card:

CORD2R	50		0.0	-100.0	0.0	0.0	0.0	1.0	+CRD1
+CRD1	0.0	-1.0	1.0						

could be referred to by an **AEROZ** bulk data card such as:

AEROZ	-50	YES	. . .	. . .					

The spline module of ZAERO will first transform the finite element model to the aerodynamic coordinates by the coordinate transformation specified in the **CORD2R** bulk data card (in this case, with an identification number of 50) and then flip the finite element model from the pilot's left-hand-side to the right-hand-side (since a negative number is specified in the ACSID field of **AEROZ**).

It should be noted that while performing a coordinate transformation for the finite element grid points, the spline module also transforms the degrees of freedom of displacements at structural grid points from the FEM coordinates to the aerodynamic coordinates. Thus, the spline matrix generated by the spline module of ZAERO establishes a direct link between the displacements at the structural finite element grid points and the aerodynamic boxes.

5.2 ZAERO Aerodynamic Modeling

To establish a ZAERO aerodynamic model for an aircraft configuration requires dividing the configuration into wing-like and body-like components. The wing-like components are the thin surfaces whose spanwise cross-sections can be represented by airfoil-like thickness distributions. These types of components include wings, tails, fins, pylons and launchers. The body-like components are the non-lifting type of bodies such as the fuselage, engines, missile bodies and stores. In this section, the modeling guidelines for wing-like components, body-like components, and the wing-body combinations are discussed.

5.2.1 Modeling Guidelines For Wing-Like Components

Wing-like components are modeled by the **CAERO7** bulk data card. **CAERO7** defines a thin sheet of unsteady vortex singularities located on the mean plane of the wing-like component. This thin sheet of unsteady vortex singularities is first divided into several strips by user-specified spanwise divisions. Each spanwise division must be parallel to the x-axis of the aerodynamic coordinates. Each strip is then divided into several boxes (called "wing boxes") by chordwise divisions specified at the root and tip chords. Each **CAERO7** bulk data card represents a wing macroelement comprising (n-1) x (m-1) wing boxes (where n = the number of spanwise divisions, and m = the number of chordwise divisions).

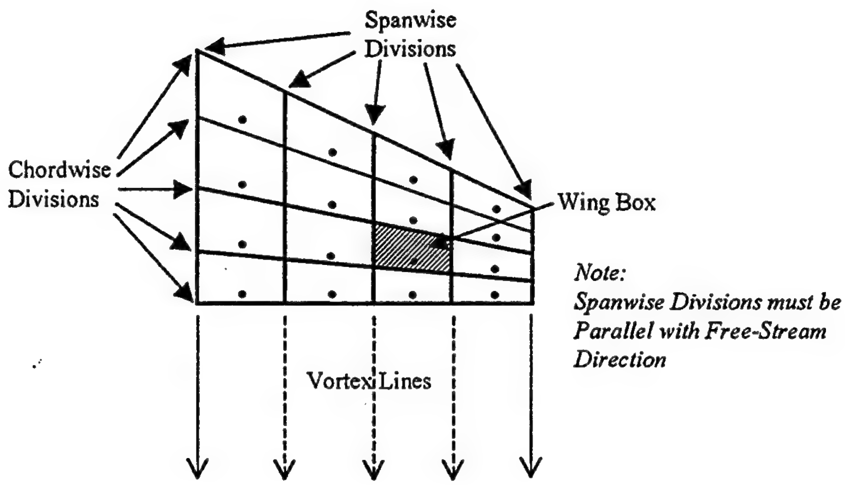


Figure 5.3 CAERO7 Wing Macroelement for Modeling Wing-Like Components.

Fig 5.3 presents a typical wing-like component modeled by the **CAERO7** macroelement. The solid circles on each wing box represent the control points at which boundary conditions are imposed. The control points which lie at the mid-span of each wing box are located at 85% of the wing box chord for subsonic Mach numbers and at 95% of the wing box chord for supersonic Mach numbers. The solid and dashed lines in the wake region of the wing-like component in Fig 5.3 represent the vortex lines generated by each strip of the **CAERO7** macroelement. The solid lines represent the so-called "strong vortex line", whereas the dashed lines represent the "weak vortex line."

These vortex lines are generated due to the discontinuity between unsteady vortex singularities for two adjacent strips. Each strip sheds two "strong vortex lines" from its side edges that start at the trailing edge and shed downstream (Fig 5.4 (a)). However, at edges shared by two adjacent strips, the strength of the two vortex lines partially cancel each other out forming a "weak vortex line" (Fig 5.4 (b)). No input is required by the user to model these unsteady vortex lines since their effects are already included as part of the vortex singularity on the wing boxes. However, due to the singular behavior of the vortex line, several restrictions must be adhered to in modeling the wing-like components by **CAERO7**.

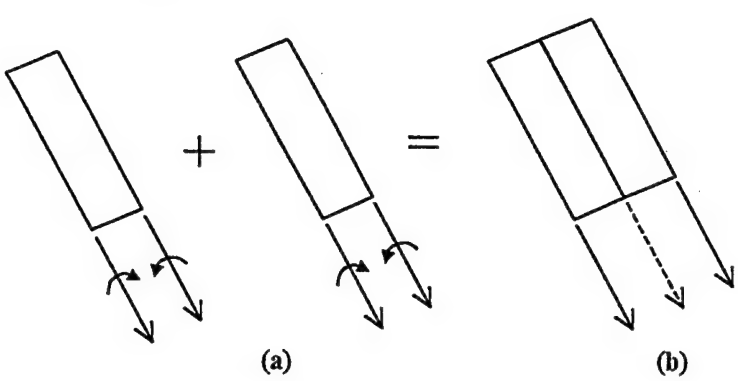
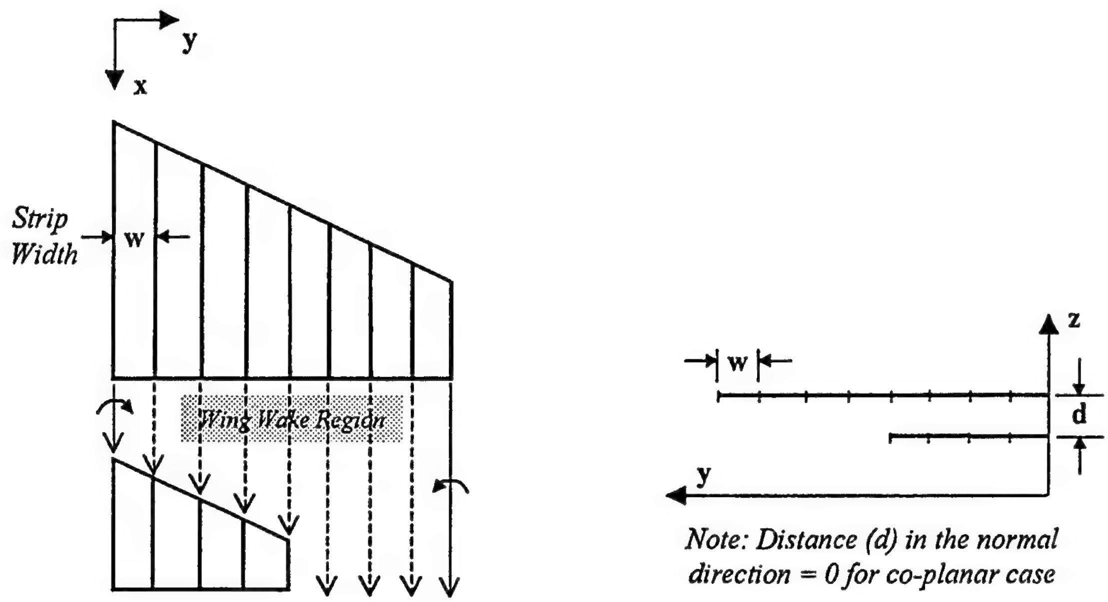


Figure 5.4 Vortex Lines Shed from CAERO7 Chordwise Strips.

- ***Alignment of spanwise divisions between coplanar CAERO7 macroelements is essential.***



(a) Top View **(b) Front View**

Figure 5.5 Alignment of Spanwise Divisions of a Wing-Tail Configuration.

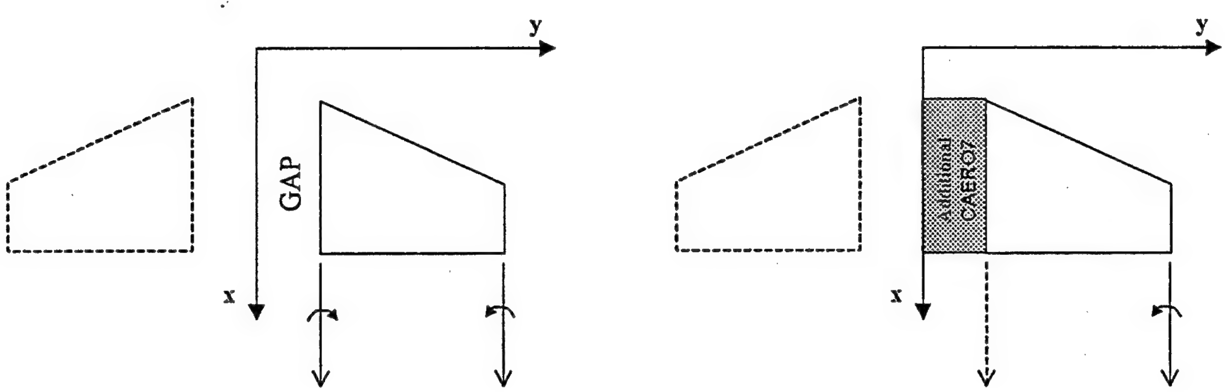
Fig 5.5 shows a wing-tail configuration modeled by two **CAERO7** macroelements. If the wing and tail are located on the same plane (coplanar), all spanwise divisions of the tail must be aligned with those of the wing. A violation of this requirement will result in the vortex lines shed from the wing cutting through the aerodynamic boxes of the tail. Since, at the vortex line, the aerodynamic influence is singular, this will yield an unrealistically large downwash effect on the tail. In fact, if the vortex line of the wing were to align with a control point on the tail, the aerodynamic matrix would be singular. This modeling restriction is still required for the case where the wing and tail are not located in the same plane and the distance (d) along the normal direction is small (i.e., $0 \leq d \leq w$). This restriction can be relaxed only if the distance is larger than the width of the strip (w) (see Fig 5.5 (b)).

- ***A gap between the right wing and the left wing should be avoided.***

Fig 5.6 shows two cases of wing-like components located on the right hand side of the pilot (represented by the solid lines) and the left hand side (represented by the dashed lines). This is a symmetric configuration (symmetric about the x-z plane), therefore, only the right-hand-side wing is modeled. However, the influence between the right wing and the left wing is properly accounted for by ZAERO. For a realistic configuration, the right and left wings are connected by a body located along the x-axis. The modeling guidelines of the wing-body combination is discussed in section 5.2.3. Should the user decide not to include the body in the model, a gap will exist between the right and left wings (Fig 5.6 (a)). Due to the absence of an adjacent strip, a "strong vortex line" will be generated at the inboard edge of the wing. This "strong vortex

line" at the inboard edge is not physical and will lead to an incorrect aerodynamic force distribution.

To avoid this problem, an additional **CAERO7** macroelement is required to bridge this gap (Fig 5.6 (b)). Since the strength of the inboard vortex line is now partially cancelled out by the vortex line generated by the additional **CAERO7**, the "strong vortex line" (shown in Fig 5.6 (a)) becomes a "weak vortex line" (shown in Fig 5.6 (b)). Therefore, the additional **CAERO7** used to fill the gap can minimize the effects of the non-physical inboard vortex line and establishes a correct model of the right as well as the left wing configuration.



(a) Incorrect Modeling **(b) Correct Modeling**

Figure 5.6 Additional CAERO7 Between the Right and Left Wings to Avoid a Gap.

5.2.2 Modeling Guidelines For Body-Like Components

The body-like components are modeled by the **BODY7** bulk data card. The discretization of the surface of the body-like component into "body boxes" is defined by the **SEGMESH** bulk data card. Therefore, the **BODY7** represents a body macroelement that includes a large number of body boxes used to model the body surface. A sheet of constant unsteady source singularity is located on each body box that simulates the aerodynamic disturbance due to the volume effects of the body.

Limitations in modeling capability due to the constant source distribution pose modeling restrictions and guidelines for the **BODY7** macroelement, as follows.

- *Modeling a wing-like component by a **BODY7** is prohibited.*

Since the source singularity can not satisfy the Kutta condition along the wing trailing edge, which is required to generate a correct force distribution on the wing-like component, modeling of wing-like components by **BODY7** will lead to incorrect aerodynamic predictions.

• ***Simplification of an arbitrary fuselage by a body-of-revolution or elliptical body is encouraged.***

(a) Arbitrary Fuselage **(b) Elliptical Body**

Figure 5.7 Simplification of an Arbitrary Body by an Elliptical Body.

Fig 5.7 (a) represents a cross-section of an arbitrary fuselage. To accurately represent this kind of arbitrary fuselage generally requires a large number of body boxes. In unsteady aerodynamics, the fuselage normally generates substantially less aerodynamic force than the wing. Modeling the fuselage with a large number of body boxes does not necessarily increase the accuracy of the results. In fact, for supersonic flows, using very large numbers of body boxes can produce an ill-conditioned aerodynamic matrix due to internal spurious Mach waves generated from the discontinuity in the constant source singularity between body boxes.

Fig 5.7 (b) shows a simplified elliptical cross-section of the arbitrary fuselage. By ensuring that the width and height of the elliptical cross-sections are equivalent to those of the arbitrary fuselage, the resulting difference in areas between the cross-sections of these two models will be small. In other words, the aerodynamic disturbance caused by the arbitrary fuselage body can be approximated by the elliptical fuselage. Numerical experience has shown that the difference in terms of flutter speeds between these two types of bodies generally is insignificant. Since modeling the elliptical body normally requires fewer body boxes than modeling a corresponding arbitrary fuselage, large amounts of computing time can be saved. Also, the "smoothness" of the elliptical body can reduce the discontinuity in the source singularity between body boxes and consequently minimizes the internal spurious Mach waves in supersonic flows.

5.2.3 Modeling Guidelines of the Wing-Body Combination

Since no vortex lines can be generated by the source singularity on body boxes, the "strong vortex line" generated by the **CAERO7** macroelement at the wing-body juncture line can not be cancelled by the **BODY7** macroelement. This creates a problem similar to that of the gap between the right and left hand wings described in section 5.2.1. However, instead of using an additional **CAERO7** to fill in the gap, an ATTCHR/ATTCHT option of the **CAERO7** bulk data card is used for the wing-body combination. The ATTCHR/ATTCHT option will automatically generate "vortex-carry-through" (VCT) wing boxes that cancel the strong vortex line at the inboard edge of the **CAERO7** macroelement. This option should be used for all wing-body junctions such as those occurring between wing and fuselages, pylons and stores, store fins and stores, vertical tails and fuselage, horizontal tails and fuselage, ventral fins and fuselage, etc. The details of this VCT option are discussed in the remarks section of the **CAERO7** bulk data card (see section 4.4).

For the single vertical tail configuration, the VCT technique should still be applied. As shown in Fig 5.8, the VCT wing boxes will cancel the vortex line at the inboard edge of the vertical tail. Since there is only one wing-like component, the "strong vortex line" along the body centerline generated by the VCT wing box still exists. However, because the vortex line is away from the body surface and the vertical tail, its adverse effects are minimal.

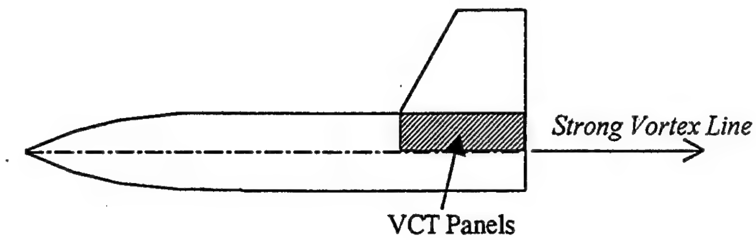


Figure 5.8 Vortex-Carry-Through Technique for a Single Vertical Tail Configuration.

Finally, it is worth mentioning that the alignment of the chordwise divisions of **CAERO7** with the axial stations of the **BODY7** at the wing-body junction is not required, but is recommended.

5.3 Modeling Requirements for Spline

Since the requirements to generate the discretized models for the structural analysis and aerodynamic analysis are subject to different engineering considerations, the grid point locations of these two models may be considerably different. This gives rise to the problem of transferring the displacements and forces between these two grid systems. Four spline methods are incorporated in the spline module of ZAERO that jointly generate a spline matrix to perform the displacement and force transferal between the structural finite element model and the ZAERO model. These four spline methods are:

- Infinite Plate Spline (IPS) Method by the **SPLINE1** bulk data card
- Beam Spline Method by the **SPLINE2** bulk data card
- Thin Plate Spline (TPS) Method by the **SPLINE3** bulk data card
- Rigid Body Attachment by the **ATTACH** bulk data card

The generation of the spline matrix is performed on a component-by-component basis. The selection of the spline method for a given component depends on the type of component in the ZAERO model (i.e. wing-like or body-like component) and the type of elements (i.e. beam or plate element) used in the finite element model. For instance, if a body-like component is modeled by a **BODY7** in the ZAERO model and if beam-type elements are used for the finite element model, then the beam spline method should be employed. If wing-like components are modeled by a **CAERO7** in the ZAERO model and plate-type elements are used for the finite element model, then the IPS method should be used. The TPS method is a 3-D spline method that can link a set of finite element grid points in 3-D space to either a **BODY7** or **CAERO7** component. The **ATTACH** bulk data card handles the special case in which a component is absent in the finite element model but is present in the ZAERO model. A typical example of such a

special case is an underwing store that is represented by a concentrated mass at a finite element grid point but is completely modeled (by a **BODY7**) in the ZAERO model.

Experience has shown that most of the errors in performing aeroelastic analysis are introduced in the spline procedure. The following modeling guidelines present several situations in which inaccurate spline results are easily introduced due to incorrect input set-up.

5.3.1 Ill-Conditioned Spline Matrix due to Coincident Finite Element Grid Point Locations

The selection of finite element grid points that are to be linked to an aerodynamic component is completely at the users discretion. These grid points are defined by **SET1** or **SET2** bulk data cards. Should two of the selected finite element grid points be located within a small tolerance of one another (tolerance set by EPS defined in the **SPLINE1** and **SPLINE3** bulk data cards), the resultant spline matrix will either be singular or ill-conditioned. This input error is automatically detected by the ZAERO spline module. However, certain scenarios exist in which this kind of input error may not be detected by the spline module.

As an example of such a scenario, Fig 5.9 shows a cross-section of a wing-like component in which the solid circles represent the finite element grid points on the upper and lower skins and the line represents the side view of a **CAERO7** macroelement. All finite element grid points appear to be well separated. If the IPS method is selected as the spline method, the spline module will project the finite element grid points onto the plane of the **CAERO7** macroelement (Fig 5.9 (b)). This plane is called the "spline plane."

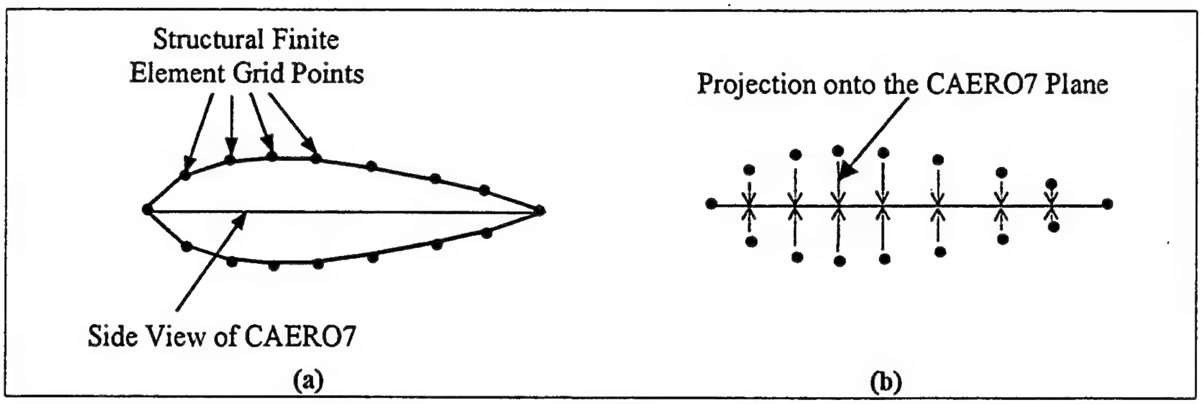


Figure 5.9 Cross-Section of a Wing-Like Component.

If the projection of two grid points on the spline plane are too close to one another, an ill-conditioned spline matrix will result. In this situation, the error condition may not be detected by the spline module. To avoid this input error, it is recommended that either the upper or lower grid points, but not both, be included in the **SET1** bulk data card.

The spline case illustrated in Fig 5.9 (a) is an ideal case for the TPS method. Since TPS is a 3-D spline method, there is no requirement to define a spline plane for grid point projection. Therefore, all upper and lower grid points can be included in the spline. However, this is true only for a thick wing-like component. As described in the remarks of the **SPLINE3** bulk data

card (section 4.4), the structural points used by the TPS method can not be located close to or within the same plane. Otherwise, an ill-conditioned spline matrix may result. For such a case, where the wing-like component thickness is very thin, the IPS method is recommended, but only with the selection of either the upper skin or lower skin grid points.

5.3.2 Spline for Discontinuous Structure

A typical case of a discontinuous structure is a control surface. The control surface creates discontinuous displacements between its side edges and the main wing as well as discontinuous slopes along the hinge line, which may have a large impact on the aeroelastic response. For this reason, it becomes important to accurately transfer these discontinuous displacements and slopes from the finite element grid points to the aerodynamic model.

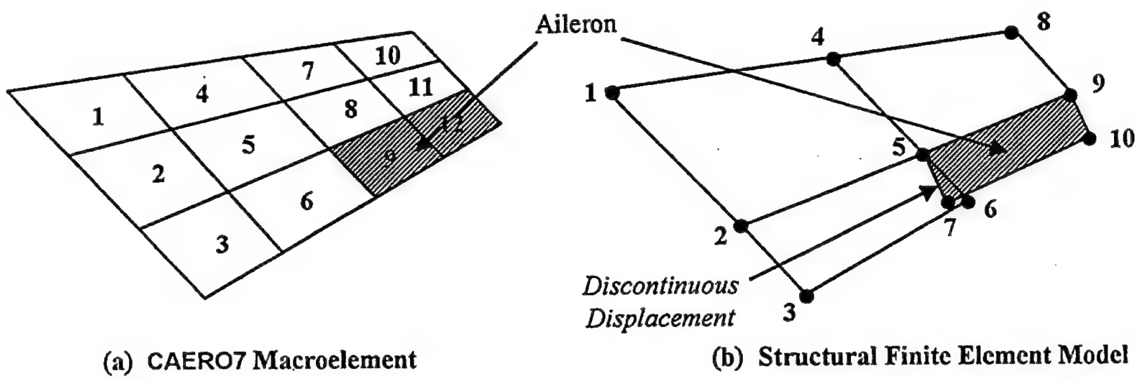


Figure 5.10 Spline of Discontinuous Structure due to a Control Surface.

Fig 5.10 (a) presents a wing with aileron configuration modeled by a **CAERO7** macroelement that includes 12 wing boxes, denoted as box 1 through box 12. The shaded area represents the aileron and its corresponding wing boxes are box 9 and box 12. The finite element model shown in Fig 5.10 (b) consists of 4 plate-type elements generated by the connection of the ten grid points (represented by the solid circles and denoted as grid points 1 through 10). Discontinuous displacement occurs between the inboard edge of the aileron and the main wing due to the discontinuous structure (between grid points 6 and 7). Because the finite element model exclusively employs plate type elements, the IPS method should be selected for this case.

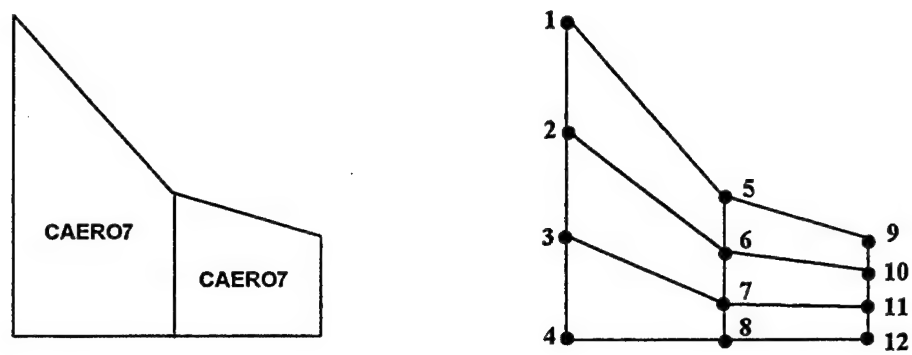
Since the IPS method is formulated based on the structural equation of an infinite plate, the continuity of displacement is inherently imposed. This indicates that if all of the finite element grid points shown in Fig 5.10 (b) are included in the spline, the resultant displacement on the **CAERO7** macroelement will be continuous. In this case, failure to transfer discontinuous displacement due to the aileron will lead to incorrect aeroelastic results.

The correct technique to be used in this spline case is to apply the IPS method on the main wing and on the aileron separately by specifying two **SPLINE1** bulk data cards. The first **SPLINE1** established for the main wing should include the wing boxes (boxes 1 - 6 plus 7, 8, 10 and 11) and finite element grid points corresponding to the main wing only (grid points 1 – 6 plus 8 and

9). Likewise, the second **SPLINE1** established for the aileron should include only those wing boxes (boxes 9 and 12) and finite element grid points associated with the aileron.

5.3.3 Ensuring Continuous Structure Across Two Adjacent CAERO7 Macroelements

One of the modeling restrictions of the **CAERO7** macroelement is that it can only represent trapezoidal types of surfaces, i.e. the inboard and outboard edges must be parallel to the x-axis of the aerodynamic coordinates (as described in section 5.1.1). Therefore, to model a non-trapezoidal type of wing-like component may require more than one **CAERO7**. Fig 5.11 (a) presents a cracked wing planform that is modeled by two **CAERO7** macroelements; one for the inboard region and one for the outboard region. The plate-type finite element model shown in Fig 5.11 (b) has 12 grid points denoted as grid point 1 through grid point 12.



(a) Aerodynamic Model **(b) Structural Finite Element Model**

Figure 5.11 Spline for a Cracked Wing Planform.

Two **SPLINE1** bulk data cards are required to spline the two **CAERO7** macroelements to the structure. The structural finite element model by itself is a continuous structure and should not incur any discontinuous slopes. Discontinuous slopes across the two **CAERO7** macroelements will result if the inboard **CAERO7** only refers to the finite element grid points located on the inboard region (grid points 1 through 8) and the outboard **CAERO7** only refers to the finite grid points located on the outboard region (grid points 5 through 12). Such discontinuous slopes across the two **CAERO7** macroelements are incorrect and will lead to incorrect aeroelastic results.

The correct technique for this spline case is to use the IPS method and to ensure that the inboard and outboard **CAERO7** macroelements refer to <u>all</u> the grid points in the finite element model (grid points 1 through 12). The infinite plates generated by the IPS method for these two **CAERO7** macroelements will then be identical leading to continuous displacements and slopes across these two wing components.

5.3.4 Accurate Rotational Structural Displacement for the Beam Spline Method

Unlike the IPS and TPS methods, which adopt only the translational displacements at the structural grid points, the beam spline method requires both the translational and rotational displacements.

Often in structural finite element analysis, the translational displacements are included as the analysis set (i.e. **ASET**) degrees-of-freedom. Since the modal analyses of finite element methods only assure accurate modal displacements for the **ASET** degrees of freedom, exclusion of the rotational displacement for **ASET** degrees-of-freedom in the beam spline method will lead to inaccurate spline results on the aerodynamic model.

5.3.5 Inaccurate Spline Results due to Extrapolation

Since structural grid points are usually placed at major load carrying components, the structural finite element model may appear to be "shorter" than the aerodynamic model. A typical case where this can occur is in modeling the structural wing torque box of a wing component. A finite element wing model that does not fully extend to the leading and trailing edges of the wing may result. Another typical case is the beam-type element model of a fuselage component. Since the nose section of a fuselage is often considered a non-structural part and, therefore, requires no structural modeling, the beam model may end up shorter than the actual length of the fuselage.

Extrapolation will be performed for the spline of aerodynamic boxes located outside the domain of the structural finite element grid points. Both of the plate spline methods (IPS and TPS) and the beam spline method incorporated within the spline module of ZAERO provide a purely linear extrapolation only if the aerodynamic box is located far away from the finite element model. Otherwise, distortions and oscillations may occur in the extrapolation regions. For this reason, extrapolation should be avoided.

To circumvent the extrapolation problem, it is recommended that extra grid points located at the leading and trailing edges of the wing or at the nose of the fuselage be added in the structural finite element model. These grid points can then be connected by rigid elements to their adjacent grid points. Thus, the problem associated with extrapolation can be avoided.

As a final note, graphical display of the displacements on the aerodynamic model for spline verification is highly recommended. It is for this reason that ZAERO provides an option to generate output files containing the aerodynamic box and corresponding displacement data. Visual inspection of the displacements for both the aerodynamic and finite element models would minimize errors caused by incorrect implementation of the spline.

5.4 Criterion of Solution Convergence for High Reduced Frequencies

ZAERO unsteady aerodynamics solves the frequency domain based unsteady small disturbance equation. The resulting unsteady pressure distribution computed by ZAERO is oscillatory in nature. The number of waves of the oscillatory pressure increases as the frequency increases. Because of this oscillatory nature, convergence of the solution with respect to the number of aerodynamic boxes of the aerodynamic model becomes an important consideration. But the precise criterion in setting up a discretized model for a converged solution in terms of reduced frequency and Mach number is unclear. To establish such a criterion, let us first examine the fundamental solution of the unsteady small disturbance equation. This fundamental solution reads:

$$e^{-ik\left(\frac{M}{\beta}\right)^2\left(\frac{x}{L}\right)} \cdot K$$

where

$$K = \frac{e^{-ik\left(\frac{M}{\beta}\right)R}}{R} \quad \text{and} \quad R = \sqrt{\left(\frac{x}{L}\right)^2 + \beta^2\left(\frac{y}{L}\right)^2 + \beta^2\left(\frac{z}{L}\right)^2} \quad \text{for } M < 1$$

$$= \frac{\cos k\left(\frac{M}{\beta}\right)R}{R} \quad \text{and} \quad R = \sqrt{\left(\frac{x}{L}\right)^2 - \beta^2\left(\frac{y}{L}\right)^2 - \beta^2\left(\frac{z}{L}\right)^2} \quad \text{for } M > 1$$

$$\beta = \sqrt{\left|M^2 - 1\right|}$$

$k = \dfrac{\omega L}{V}$ is the reduced frequency, ω is the circular frequency, M is the freestream Mach number and L is the reference length.

Two observations can be concluded by examining the fundamental solution:

(1) The oscillatory pressure distribution has more "waviness" in the x-direction than other directions due to the exponential term $e^{-ik\left(\frac{M}{\beta}\right)^2\left(\frac{x}{L}\right)}$. This suggests that the discretized aerodynamic model should have more aerodynamic boxes along the x-direction (i.e. chordwise boxes) than in other directions.
(2) The number of waves that can be generated by the fundamental solution is dominated by the reduced frequency k and the Mach number M.

The impact of the reduced frequency on the solution convergence is generally understood. But the parameter (M/β) indicates that the Mach number also has a strong influence on the solution convergence with respect to the number of aerodynamic boxes, particularly when the Mach number approaches sonic speed ($M \approx 1$, so $\beta \approx 0$) where the number of waves of the oscillatory pressure distribution can increase dramatically. This can be seen by comparing the pressure distributions at a fixed reduced frequency for various Mach numbers. Fig 5.12 shows the real part of the 2-D unsteady pressure distribution along the chord at M=1.11, 1.25 and 2.5 as computed by Jordan's exact theory. For a given reduced frequency (k=1.0) and unsteady motion (in this case plunging motion), it is seen that the pressure distribution becomes highly oscillatory as the Mach number approaches unity, indicating that more chordwise boxes are required for solution convergence.

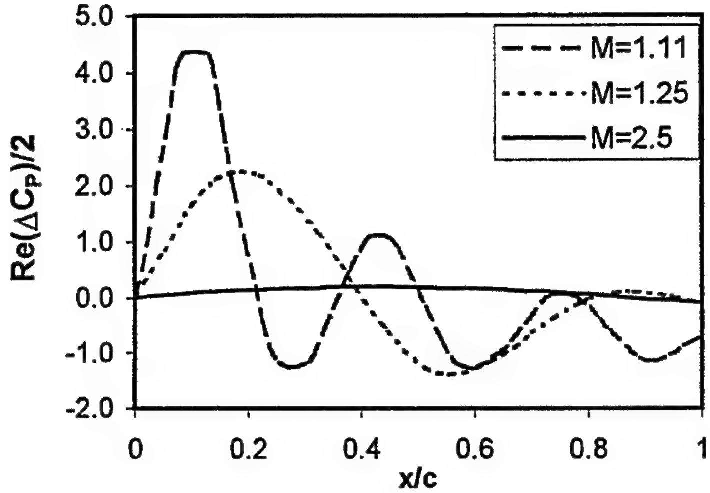


Figure 5.12 2-D Unsteady Pressure Distributions due to Plunging Motion at k=1.0 and M=1.11, 1.25 and 2.5 as Computed by Jordan's Exact Theory.

Based on the above two observations, one can establish a criterion that defines a minimum chord length of an aerodynamic box for solution convergence. For a given rectangular wing with a chord length of c, let us assume $k\left(\frac{M}{\beta}\right)^2 = \pi$ and $L = \frac{c}{2}$ so that the wavelength of the imaginary part of $e^{-ik\left(\frac{M}{\beta}\right)^2\left(\frac{x}{L}\right)}$ is one chord length, as shown in Fig 5.13 (a).

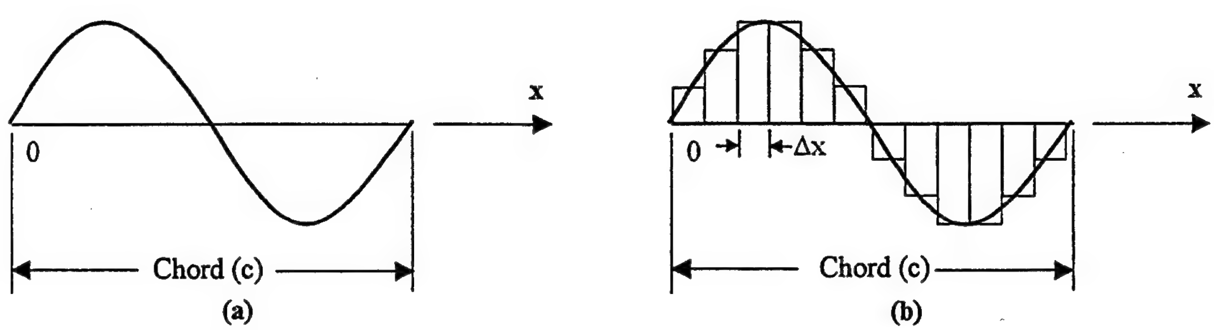


Figure 5.13 Convergence Criterion of the Minimum Number of Boxes Along the X-Direction.

The real part also has one cosine wave, but its convergence criterion would be the same as that of the imaginary part. For a good representation of one sine wave, it is assumed that approximately 12 chordwise boxes are required (Fig 5.13 (b)). This gives the required minimum chord length of the box as:

$$\Delta x < \frac{c}{12} \quad \text{for} \quad k\left(\frac{M}{\beta}\right)^2 = \pi \quad \text{and} \quad L = \frac{c}{2}$$

This minimum chord length requirement can be generalized for any $k\left(\frac{M}{\beta}\right)^2$ as

$$\Delta x < \frac{c}{12} \frac{\pi}{k\left(\frac{M}{\beta}\right)^2} \quad \text{for} \quad L = \frac{c}{2}$$

or

$$\Delta x < 0.08 \left(\frac{V}{f}\right) \frac{\pi}{\left(\frac{M}{\beta}\right)^2} \quad \text{for} \quad L = \frac{c}{2} \quad \text{where } f \text{ is the frequency in Hz.}$$

The unsteady pressure distributions computed by Jordan's exact theory shown in Fig 5.12 can be used to test the above criterion. For M=1.11 and k=1.0, the minimum chord length is approximately Δx=1/0.05. This implies that a converged solution would require at least 20 equally distributed chordwise boxes. Fig 5.14 presents the unsteady pressure distribution at the center strip of a rectangular wing computed by ZONA7.

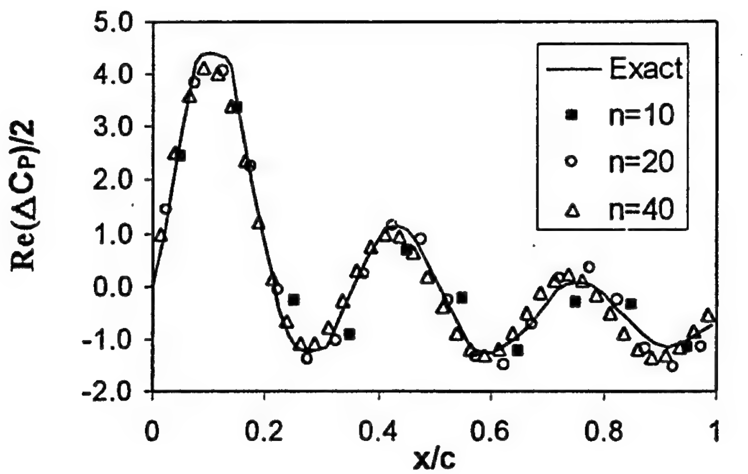


Figure 5.14 Comparison of the ZONA7 Solution with Jordan's Exact Theory at M=1.11, k=1.0.

To validate the above criterion, let us consider a rectangular wing with a large aspect ratio value so that the Mach waves emanating from the wing tip do not intersect with the center strip. In this fashion, the solution obtained at the center strip is equivalent to a 2-D solution in supersonic flow. The rectangular wing is discretized into 10, 20 and 40 chordwise boxes. Fig 5.14 shows that the pressure distribution obtained by the 10 chordwise boxes (denoted by the solid squares) does not compare satisfactorily with Jordan's solution. This is expected since the 10 chordwise box model falls below the established criterion (i.e. a minimum of 20 chordwise boxes is required for M=1.11 and k=1.0).

The validity of the above criterion can be demonstrated by the good comparisons of the pressure distribution obtained by the 20 chordwise box model (denoted by the open circles in Fig 5.14). Furthermore, no significant improvement in the comparison with Jordan's exact theory between

the 20 chordwise box model and the 40 chordwise box model (denoted by the open triangles in Fig 5.14) can be seen, indicating that the solution is already converged at the 20 chordwise box model.

At k=0.0, the unsteady aerodynamic solution reduces to the steady solution. Generally, at least 4 chordwise boxes per chord length is required to have a satisfactory solution for steady aerodynamics.

The following summarizes the criterion established for solution convergence.

- In terms of oscillating frequency f in Hz:

$$\Delta x < 0.08 \left(\frac{V}{f}\right) \frac{\pi}{\left(\frac{M}{\beta}\right)^2} \quad \text{for} \quad L = \frac{c}{2} \quad \text{where } f \text{ is the frequency in Hz.}$$

- In terms of reduced frequency:

$$\Delta x < 0.08\ c\ \frac{\pi}{k\left(\frac{M}{\beta}\right)^2} \quad \text{for} \quad L = \frac{c}{2} \quad \text{and} \quad k = \frac{(2\pi f)L}{V}.$$

where the minimum number of boxes per chord length must be greater than or equal to 4.

5.5 ZTAIC Steady Pressure Input

The following bulk data input cards are required for the ZAERO transonic method (i.e ZTAIC method) and are listed from left to right in order of calling sequence.

CAERO7 ⟶ **ZTAIC** ⟶ **MACHCP** ⟶ **CHORDCP**

CAERO7 describes the wing component, **ZTAIC** calls the transonic method, **MACHCP** establishes the Mach number and steady pressure relations, and **CHORDCP**is used to input the upper and lower steady pressure on the wing component.

The ZTAIC method performs an inverse airfoil design that generates an airfoil surface based on the user-input steady pressure. This designed airfoil surface is used to generate the unsteady transonic pressure distribution. Therefore, the user should treat this steady pressure input as geometry input since the steady pressure input leads to an airfoil surface. *(See the ZAERO Theoretical Manual for a detailed description of the ZTAIC method).* For this reason, the **ZTAIC**, **MACHCP** and **CHORDCP** bulk data cards are all defined as a part of the **CAERO7** macroelement. The ZTAIC input process is outlined in Fig 5.15.

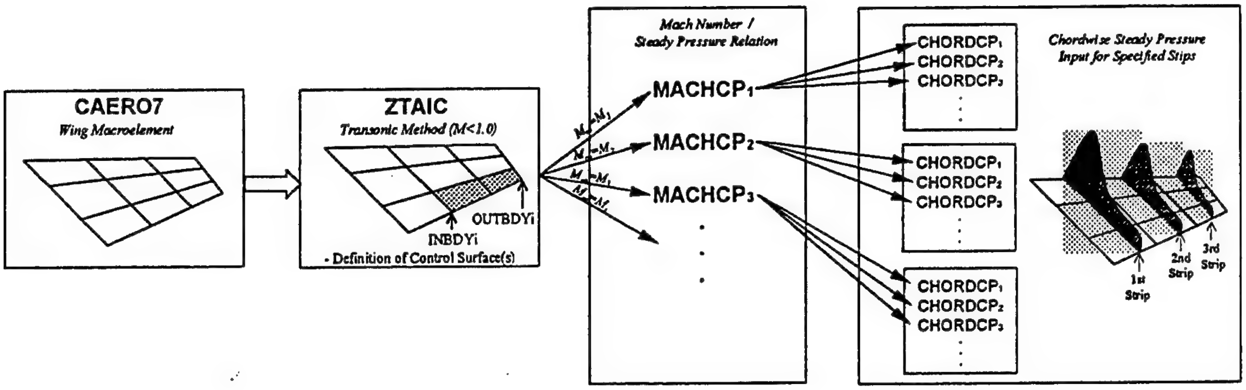


Figure 5.15 ZTAIC Input Process.

- *Running ZTAIC*

In order to execute the ZTAIC method within ZAERO, the following items must be present in the ASTROS* input deck:

1. METHOD entry of **MKAEROZ** bulk data card must be set to 1
2. MACH entry of **MKAEROZ** bulk data card must be less than 1.0
3. One MACH entry of an **MKAEROZ** bulk data card must match the MACH entry of the **MACHCP** bulk data cards
4. **CAERO7** bulk data card must refer to a **ZTAIC** bulk data card id in the ZTAIC entry field
5. **ZTAIC** bulk data card must refer to at least one (1) **MACHCP** bulk data card which in turn must refer to at least one (1) **CHORDCP** bulk data card

It is important to note item #3 above. The Mach number of an **MKAEROZ** bulk data card must be the same as the Mach numbers listed in the **MACHCP** bulk data cards or the code will terminate with errors.

- *Mach Numbers in* **MACHCP**

Only six (6) freestream Mach numbers (i.e. six **MACHCP**) are allowed within a **ZTAIC** bulk data card. The program will not interpolate steady pressures at other Mach numbers.

- *Spanwise Strip Indicies in* **MACHCP**

Normally the **MACHCP** card includes all of the spanwise strip indicies associated with its corresponding **CAERO7** wing macroelement. For any spanwise strip indicies not appearing in the **MACHCP** bulk data card entry, a linear unsteady pressure as computed by the ZONA6 method will be adopted on those strips.

- *Control Surface Definition in ZTAIC*

If the structural finite element model contains a discontinuous structure such as a control surface, then this discontinuous structure will generate discontinuity in the mode shape. Such a mode

shape, associated with a control surface, is called a flap mode. The definition of the control surfaces specified in the **ZTAIC** bulk data card is used to generate the unsteady pressure due to this flap mode.

On the other hand, an **AESURFZ** bulk data card defines an aerodynamic control surface that may not be present in the structural finite element model. Therefore, the control surface defined by the **ZTAIC** card is not required to be associated with that of the **AESURFZ** bulk data card.

5.6 Airfoil Thickness Input by PAFOIL7 Bulk Data Card for ZONA7U

For linear unsteady aerodynamic methods (ZONA6 and ZONA7) the airfoil thickness effects is uncoupled from the unsteady aerodynamics, i.e all wing-like components are modeled by "flat-plates" and have no requirements for airfoil thickness input.

However, the thickness effect is of importance for hypersonic aerodynamic methods, such as ZONA7U. Therefore the **PAFOIL7** bulk data card is only used when ZONA7U is selected.

In order to execute the ZONA7U method within ZAERO, the following items must be present in the ASTROS* input deck:

1. METHOD entry of **MKAEROZ** bulk data card must be set to 1
2. MACH entry of **MKAEROZ** bulk data card must be greater than 1.0
3. **CAERO7** bulk data card must refer to a **PAFOIL7** bulk data card id in the PAFOIL7 entry field

If zero thickness distribution is specified in the **PAFOIL7** bulk data card, then the result of ZONA7U will be identical to that of ZONA7 (i.e. linear result).

6.0 ZAERO OUTPUT DESCRIPTION

Table 3.2 in Section 3.0 presents output requests that can be made from ZAERO. By default (i.e. PRINT flag values set to zero), no aerodynamic geometry or aerodynamic quantities are output by ZAERO. This is analogous to the ASTROS output style and is structured to avoid the output of vast amounts of data which may not be of interest to the user. Although the ZAERO module replaces the older aerodynamic methods available in ASTROS, the ASTROS* output for static aeroelasticity and flutter remain unchanged.

This section presents the user requested ZAERO output based on PRINT flag values set by the **MKAEROZ, FLUTTER** and **TRIM** bulk data cards.

6.1 Geometric Output of the Aerodynamic Model

- Output generated by **MKAEROZ** (PRINT < 0) -

```
MKAEROZ ID=      10 MACH =   0.800, NUMBER OF REDUCED FREQUENCIES (K) =   19, K=
    0.0010    0.2200    0.2300    0.2400    0.2500    0.2600    0.2800    0.3000    0.3200    0.3400
    0.3600    0.4000    0.4200    0.5000    0.6000    0.7000    0.8000    0.9000    1.0000
  REFC=  200.000, REFB=     1.000, REFS=     1.000, XCG =     0.000, YXG =     0.000, ZCG =     0.000

 AERODYNAMIC MODEL IS SYMMETRIC ABOUT X-Z PLANE
```

MKAEROZ ID	= Identification number of current **MKAEROZ** card
MACH	= Free stream Mach number
K	= Reduced frequencies
REFC	= Reference chord length*
REFB	= Reference span length*
REFS	= Reference area*
XCG,YCG,ZCG	= X, Y, Z location about which stability derivative calculations are made (about reference grid GREF)*

* These items are defined by the **AEROZ** bulk data card

```
TOTAL NUMBER OF AERODYNAMIC GRID POINTS=     171. X,Y AND Z ARE DEFINED IN THE BASIC COORD.
EXTERNAL GRID ID  INTERNAL GRID ID  ACOORD ID          X          Y          Z
          100                 1            20  -100.000      0.000      0.000
          101                 2            20  -100.000      0.000      0.000
          102                 3            20  -100.000      0.000      0.000
          103                 4            20  -100.000      0.000      0.000
                              .
                              .
                              .
```

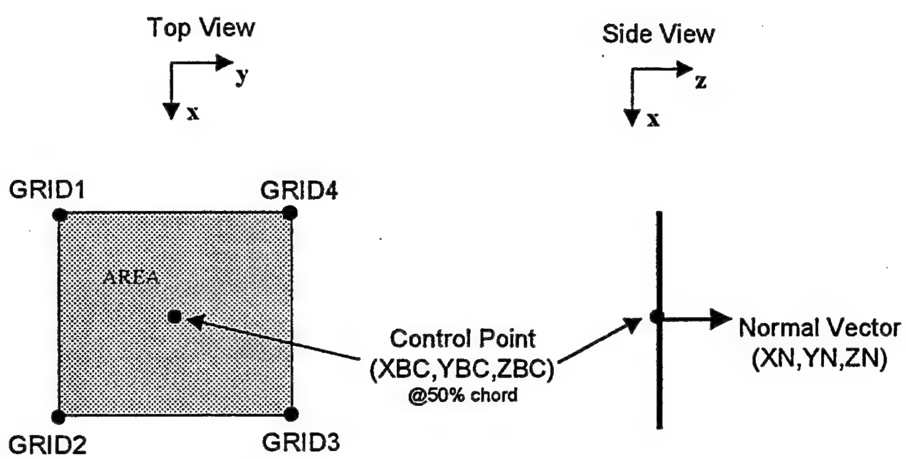
EXTERNAL GRID ID	= User defined aerodynamic grid identification number starting from the lowest identification number among all CAERO7 or BODY7 bulk data cards
INTERNAL GRID ID	= ZAERO generated internal identification number of aerodynamic grid starting from 1 and ending at the total numbers of aerodynamic grids
ACOORD ID	= Identification number of aerodynamic coordinate system
X,Y,Z	= X, Y, Z aerodynamic grid point location in the basic coordinate system

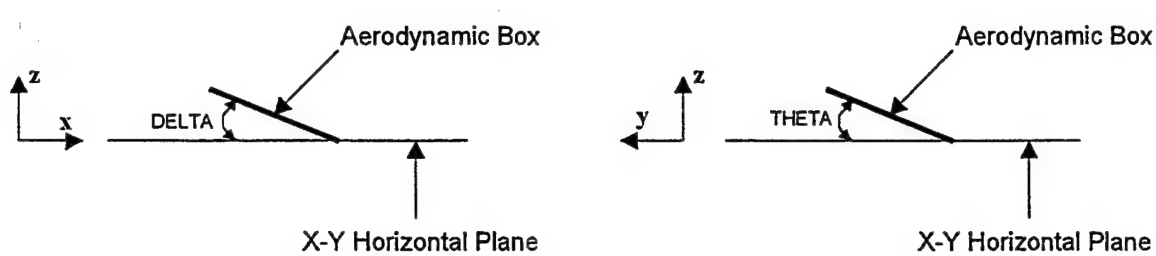
---

6.1.1 Body Components (BODY7)

```
BODY7 ID=     100, LABEL=BODY    , NOSE LOCATION=  -100.000     0.000     0.000, BODY LENGTH=   200.000, NUMBER OF BOXES=   80
BODY7 BOX GEOMETRY DATA: GRID 1-4: CORNER GRID ID, XBC,YBC,ZBC: CONTROL POINT LOCATION
NX NY NZ: NORMAL VECTOR, THETA & DELTA: DIHEDRAL & INCLINATION ANGLES(DEG).
TYPE=0: REGULAR PANEL. TYPE=1: INLET PANEL. TYPE=2: WAKE PANEL
  INTID   EXTID  GRID 1  GRID 2  GRID 3  GRID 4     XBC     YBC     ZBC      NX      NY      NZ    AREA   THETA   DELTA    TYPE
      1     100     101     106     105     100 -93.333   2.357  -5.690  -0.679   0.281  -0.679  52.101-157.500  42.734       0
      2     101     102     107     106     101 -93.333   5.690  -2.357  -0.679   0.679  -0.281  52.101-112.500  42.734       0
      3     102     103     108     107     102 -93.333   5.690   2.357  -0.679   0.679   0.281  52.101 -67.500  42.734       0
      4     103     104     109     108     103 -93.333   2.357   5.690  -0.679   0.281   0.679  52.101 -22.500  42.734       0
      5     104     106     111     110     105 -84.568   4.880 -11.781  -0.543   0.321  -0.776 123.049-157.500  32.891       0
                                                                  .
                                                                  .
                                                                  .
```

BODY7 ID = Identification number of a **BODY7** bulk data card
LABEL = Label of **BODY7** bulk data card
NOSE LOCATION= X,Y,Z location of the **BODY7** nose (i.e. 1st X-location defined by the first **SEGMESH** bulk data card) with respect to the basic coordinate system
BODY LENGTH = Maximum length of the body along the freestream direction
NUMBER OF BOXES = Total number of aerodynamic boxes for the current **BODY7**
<u>BODY7 BOX GEOMETRY DATA</u> – (see the following figures)
GRID 1-4 = Aerodynamic corner grid point identification numbers (EXTERNAL)
XBC,YBC,ZBC = Aerodynamic box control point location
NX,NY,NZ = Aerodynamic box normal vector
THETA = Aerodynamic box inclination angle in degrees (Y-Z plane)
DELTA = Aerodynamic box inclination angle in degrees (X-Z plane)
TYPE = Type of aerodynamic box defined in the **BODY7** bulk data card (=0 regular box, =1 inlet box, =2 wake box)





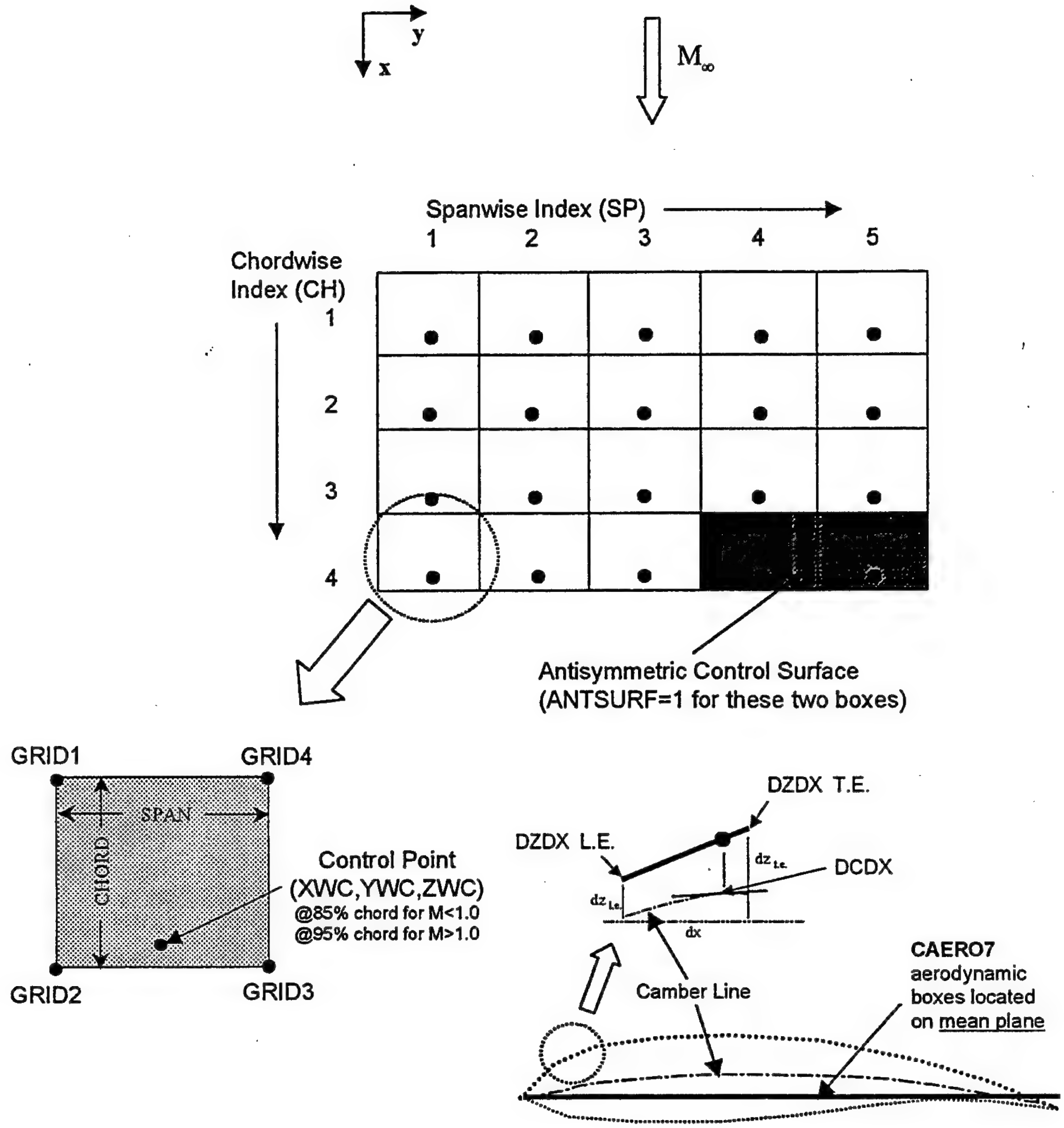
6.1.2 Wing Components (CAERO7)

```
CAERO7 ID=      10, LABEL=WING    , SPAN & CHORDWISE DIVISIONS= 6  11, NORMAL VECTOR=   0.000   0.000   1.000, NUMBER OF BOXES=   50
CAERO7 BOX GEOMETRY DATA: GRID 1-4: CORNER GRID ID, XWC,YWC,ZWC:CONTROL POINT LOCATION, SP:SPANWISE INDEX, CH:CHORDWISE INDEX
CHORD:MID-CHORD LENGTH, DCDX:CAMBER SLOPE, DZDX LE & TE:HALF THICKNESS SLOPES AT L.E. & T.E. EDGES, SYMSURF,ANTSURF:SYM&ANTI AESURFZ
 INTID   EXTID  GRID 1  GRID 2  GRID 3  GRID 4 SP CH     XWC     YWC     ZWC   CHORD    SPAN    DCDX DZDX LE DZDX TE SYMSURF ANTSURF
    81      10      10      11      22      21  1  1  13.075  37.000   0.000   9.500  14.000  0.0770  0.7462  0.1621       0       0
    82      11      11      12      23      22  1  2  22.575  37.000   0.000   9.500  14.000  0.0503  0.1621  0.0565       0       0
    83      12      12      13      24      23  1  3  32.075  37.000   0.000   9.500  14.000  0.0286  0.0565 -0.0010       0       0
    84      13      13      14      25      24  1  4  41.575  37.000   0.000   9.500  14.000  0.0043 -0.0010 -0.0369       0       0
    85      14      14      15      26      25  1  5  51.075  37.000   0.000   9.500  14.000 -0.0090 -0.0369 -0.0643       0       0
                                                                            .
                                                                            .
                                                                            .
```

CAERO7 ID = Identification number of a **CAERO7** bulk data card
LABEL = Label of **CAERO7** bulk data card
SPAN AND CHORDWISE
DIVISIONS = Number of spanwise and chordwise divisions of the current lifting surface, respectively
NORMAL VECTOR = Normal vector to the current lifting surface
NUMBER OF BOXES = Total number of aerodynamic boxes for the current **CAERO7**
<u>CAERO7 BOX GEOMETRY DATA</u> – (see the following figures)
GRID 1-4 = Aerodynamic corner grid point identification numbers (EXTERNAL)
SP = Spanwise index of current aerodynamic box
CH = Chordwise index of current aerodynamic box
XWC,YWC,ZWC = Aerodynamic box control point location
CHORD = Aerodynamic box mid-chord length
SPAN = Aerodynamic box mid-span length
DCDX = Aerodynamic box camber slope at the control point (dc/dx)*
DZDX LE/TE = Aerodynamic box leading/trailing edge thickness slopes (dz/dx)*
SYMSURF/
ANTSURF = Identifies whether aerodynamic box belongs to a symmetric or antisymmetric control surface**

(=0 <u>is not</u> part of a control surface, =1 <u>is</u> part of a control surface)

* computed if airfoil cross sections are specified by the **PAFOIL7** bulk data card
** computed if control surface is defined by the **AESURFZ** bulk data card



Airfoil Cross Section
(thickness/camber specified by **PAFOIL7**)

6.2 Interpolated Mode Shapes

- Output generated by **FLUTTER** (PRINT $\geq$ 3) -

Aerodynamic box interpolated mode shapes are generated if PRINT=3 on the **FLUTTER** bulk data card. Six degrees of freedom are defined for each mode. These are X, Y, and Z displacements of the aerodynamic box control points and aerodynamic box slopes in the X, Y, and Z directions with respect to the basic system X-axis. Note that aerodynamic boxes not splined to the structural model will have no displacements.

INTERPOLATED , 5 MODES ON AERODYNAMIC BOXES

	MODE NO: 1						MODE NO: 2					
INT ID	T1	T2	T3	D(T1)/DX	D(T2)/DX	D(T3)/DX	T1	T2	T3	D(T1)/DX	D(T2)/DX	D(T3)/DX
1	7.72E-04	2.60E-03	-9.40E-02	-1.08E-09	-1.10E-04	4.70E-03	9.88E-04	3.33E-03	-1.46E-01	-1.38E-09	-1.41E-04	3.24E-03
2	7.72E-04	1.55E-03	-4.91E-02	-1.44E-09	-1.10E-04	4.80E-03	9.88E-04	1.99E-03	-1.19E-01	-1.84E-09	-1.41E-04	2.78E-03
3	7.72E-04	5.05E-04	-3.11E-03	-1.23E-09	-1.10E-04	4.80E-03	9.88E-04	6.47E-04	-8.72E-02	-1.57E-09	-1.41E-04	4.32E-03
4	7.72E-04	-5.42E-04	4.06E-02	-3.06E-10	-1.10E-04	4.46E-03	9.88E-04	-6.94E-04	-2.84E-02	-3.91E-10	-1.41E-04	8.10E-03
5	7.72E-04	-1.59E-03	8.52E-02	-1.11E-09	-1.10E-04	5.10E-03	9.88E-04	-2.03E-03	6.02E-02	-1.42E-09	-1.41E-04	1.03E-02
6	7.72E-04	-2.64E-03	1.39E-01	-2.39E-10	-1.10E-04	6.32E-03	9.88E-04	-3.38E-03	1.66E-01	-3.06E-10	-1.41E-04	1.22E-02

.
.
.

INT ID	=	Aerodynamic box internal identification number
T1	=	Aerodynamic box control point displacement in the X-direction*
T2	=	Aerodynamic box control point displacement in the Y-direction*
T3	=	Aerodynamic box control point displacement in the Z-direction*
D(T1)/DX	=	Aerodynamic box slope in the X-direction with respect to the X-axis*
D(T2)/DX	=	Aerodynamic box slope in the Y-direction with respect to the X-axis*
D(T3)/DX	=	Aerodynamic box slope in the Z-direction with respect to the X-axis*

* relative to the basic system

6.3 Steady Pressure Results

- *Output Generated By* TRIM (PRINT +/- 2) -

Steady pressure results for lifting surfaces and bodies are obtained through an ASTROS* steady aerodynamics request in the case control [i.e. via SAERO SYMMETRIC (TRIM=XX)]. Symmetric or antisymmetric results can be generated. Steady pressure for all aerodynamic boxes may be printed along with force and moment coefficients of the entire aerodynamic model.

6.3.1 For Body Components

STEADY RESULTS ON BODY AT MACH= 0.800 AOA= 0.000

EXTERNAL ID	STRENGTH	U	V	W	CP COEFF	LOCAL MACH	CP
100	0.5617E+00	-0.5941E+00	0.1437E+00	-0.3464E+00	-0.2475E+01	0.3617E+00	0.7753E+00
101	0.5616E+00	-0.5940E+00	0.3467E+00	-0.1432E+00	-0.2474E+01	0.3619E+00	0.7750E+00
102	0.5613E+00	-0.5938E+00	0.3466E+00	0.1440E+00	-0.2474E+01	0.3622E+00	0.7747E+00
103	0.5611E+00	-0.5936E+00	0.1435E+00	0.3469E+00	-0.2474E+01	0.3624E+00	0.7744E+00
104	0.5752E+00	-0.3447E+00	0.1624E+00	-0.3915E+00	-0.2260E+01	0.5957E+00	0.4160E+00
105	0.5750E+00	-0.3445E+00	0.3918E+00	-0.1618E+00	-0.2259E+01	0.5959E+00	0.4157E+00

.
.
.

MACH	=	Free stream Mach number
AOA	=	Angle-of-attack (in degrees)
EXTERNAL ID	=	Aerodynamic box external identification number
STRENGTH	=	Aerodynamic box singularity source strength
U,V,W	=	Perturbation velocities (x,y,z directions, respectively) at the control point
CP COEFF	=	Pressure coefficient of aerodynamic box*
LOCAL MACH	=	Local Mach number*
CP	=	Aerodynamic box pressure coefficient*

* defined as follows:

$$C_{P_{coeff}} = -2.0\left[1.0+0.2M^2\left(1.0-u^2\cos\alpha+v^2+w^2\sin\alpha\right)\right]^{2.5}$$

$$M_{local} = M\left[\frac{1.0-C_P}{1.0+0.2M^2 C_P}\right]^{0.5}$$

If $M<0.005$ then

$$C_P = 1.0-u^2\cos\alpha+v^2+w^2\sin\alpha$$

else

$$C_P = \frac{2}{\gamma M^2}\left\{\left[1.0+0.2M^2\left(1.0-u^2\cos\alpha+v^2+w^2\sin\alpha\right)\right]^{3.5}-1.0\right\}.$$

where

M = free stream Mach number
γ = ratio of specific heats (=1.4)
α = angle-of-attack to free stream
u,v,w = perturbation velocities

6.3.2 For Wing Components

-- Symmetric Analysis

Steady aerodynamic forces are generated for the entire aerodynamic model per unit value *of all allowable states in terms of structural accelerations and aerodynamic parameters.*

```
STEADY AERODYNAMICS, MACH=  0.8000 MINDEX=    1 METHOD=    0


SYMMETRIC AERODYNAMIC STABILITY DERIVATIVES OF RIGID CONFIGURATION AT MACH= 0.8000. NUMBER OF CONTROL SURFACES=    0
REFC=    200.0000 REFB=       1.0000 REFS=          1.0000 MOMENT CENTER(X,Y,Z)=      0.0000      0.0000      0.0000
    STATES     UNIT VALUE          CL          CD          CS          CMX         CMY         CMZ
    NX         0.1000E+01  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    NZ         0.1000E+01  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    QACCEL     0.1000E+01  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    THKCAM     0.1000E+01  0.1297E+04 -0.1713E+03  0.0000E+00  0.0000E+00 -0.4955E+03  0.0000E+00
    ALPHA      0.1000E+01  0.5838E+03 -0.5363E-01  0.0000E+00  0.0000E+00 -0.2730E+02  0.0000E+00
    QRATE      0.1000E+01  0.2768E+05  0.1883E+01  0.0000E+00  0.0000E+00 -0.6205E+04  0.0000E+00
```

Steady aerodynamic pressures on all aerodynamic boxes are generated per unit value *of all allowable states in terms of structural accelerations and aerodynamic parameters.*

```
***** STEADY RIGID AERODYNAMIC PRESSURE OF TRIM PARAMETERS FOR MINDEX=       1,MACH=  0.8000,METHOD=  0,TRIMFLT ID=       0 *****


          PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT
          NX       /  NZ       /  QACCEL   /  THKCAM   /  ALPHA    /  QRATE    /
  EXT ID   1.00000     1.00000     1.00000     1.00000     1.00000     1.00000
     100  0.0000E+00  0.0000E+00  0.0000E+00  0.6125E-01  0.2641E-01 -0.1227E+03
     101  0.0000E+00  0.0000E+00  0.0000E+00  0.6123E-01  0.1092E-01 -0.5070E+02
     102  0.0000E+00  0.0000E+00  0.0000E+00  0.6121E-01 -0.1097E-01  0.5099E+02
     103  0.0000E+00  0.0000E+00  0.0000E+00  0.6119E-01 -0.2644E-01  0.1228E+03
     104  0.0000E+00  0.0000E+00  0.0000E+00  0.1707E+00  0.2922E-01 -0.1137E+03
     105  0.0000E+00  0.0000E+00  0.0000E+00  0.1705E+00  0.1208E-01 -0.4701E+02
     106  0.0000E+00  0.0000E+00  0.0000E+00  0.1703E+00 -0.1214E-01  0.4727E+02
                                                        .
                                                        .
                                                        .
```

— Antisymmetric Analysis

```
STEADY AERODYNAMICS, MACH=  0.8000 MINDEX=    1 METHOD=    0

ANTI-SYMMETRIC AERODYNAMIC STABILITY DERIVATIVES OF RIGID CONFIGURATION AT MACH= 0.8000. NUMBER OF CONTROL SURFACES=        0
REFC=    200.0000 REFB=       1.0000 REFS=        1.0000 MOMENT CENTER(X,Y,Z)=      0.0000      0.0000      0.0000
    STATES     UNIT VALUE           CL          CD          CS          CMX         CMY         CMZ
    NY         0.1000E+01  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    PACCEL     0.1000E+01  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    RACCEL     0.1000E+01  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00
    BETA       0.1000E+01  0.0000E+00  0.0000E+00 -0.4538E+02  0.2436E-03  0.0000E+00  0.8861E+04
    PRATE      0.1000E+01  0.0000E+00  0.0000E+00 -0.1083E+05 -0.1623E+09  0.0000E+00 -0.6113E+06
    RRATE      0.1000E+01  0.0000E+00  0.0000E+00 -0.2945E+06  0.1513E+01  0.0000E+00 -0.1898E+08


STEADY AERODYNAMICS, MACH=  0.8000 MINDEX=    1 METHOD=    0

***** STEADY RIGID AERODYNAMIC PRESSURE OF TRIM PARAMETERS FOR MINDEX=       1,MACH=  0.8000,METHOD=  0,TRIMFLT ID=       0 *****

        PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT  PARAM/UNIT
        NY       /  PACCEL   /  RACCEL   /  BETA     /  PRATE    /  RRATE    /
  EXT ID  1.00000     1.00000     1.00000     1.00000     1.00000     1.00000
     100  0.0000E+00  0.0000E+00  0.0000E+00  0.1078E-01 -0.4582E-02 -0.5155E+02
     101  0.0000E+00  0.0000E+00  0.0000E+00  0.2601E-01 -0.9335E-03 -0.1244E+03
     102  0.0000E+00  0.0000E+00  0.0000E+00  0.2599E-01  0.1333E-01 -0.1243E+03
     103  0.0000E+00  0.0000E+00  0.0000E+00  0.1076E-01  0.9683E-02 -0.5148E+02
     104  0.0000E+00  0.0000E+00  0.0000E+00  0.1186E-01 -0.1932E-01 -0.4815E+02
     105  0.0000E+00  0.0000E+00  0.0000E+00  0.2861E-01 -0.1183E-01 -0.1162E+03
     106  0.0000E+00  0.0000E+00  0.0000E+00  0.2860E-01  0.3745E-01 -0.1161E+03
                                                            .
                                                            .
                                                            .
```

MACH	= Free stream Mach number
MINDEX	= Internal identification number of **MKAEROZ** bulk data card (not external identification number specified in the **MKAEROZ** bulk data card!)
METHOD	= ZONA aerodynamic method used (specified by the **MKAEROZ** bulk data card)
REFC	= Reference chord length*
REFB	= Reference span length*
REFS	= Reference area*
MOMENT CENTER (X,Y,Z)	= X, Y, Z location about which moment calculations are made (about reference grid GREF)*
TRIMFLT ID	= Identification number of a **TRMFLT** bulk data card specifying steady aerodynamic mean flow conditions (Angle-of-attack, side-slip angle, pitch rate, etc.)
CL,CD,CS	= Lift, drag, side force coefficients, respectively
CMX,CMY,CMZ	= Moment coefficients about CENTER(X,Y,Z)
EXT ID	= Aerodynamic box external identification number
SYMMETRIC STATES	
NX	= Longitudinal acceleration**
NZ	= Vertical acceleration (load factor)**
QACCEL	= Pitch acceleration**
THKCAM	= Thickness and camber and control surfaces (in degrees)
ALPHA	= Angle-of-attack (in degrees)
QRATE	= Pitch rate (in radians per second)
ANTISYMMETRIC STATES	
NY	= Side-slip acceleration**
PACCEL	= Roll acceleration**
RACCEL	= Yaw acceleration**
BETA	= Yaw angle (in degrees)
PRATE	= Roll rate (in radians per second)
RRATE	= Yaw rate (in radians per second)

* These items are defined by the **AEROZ** bulk data card

** Note that accelerations do not produce steady aerodynamic forces

6.4 Unsteady Pressure Results

- Output generated by **FLUTTER** (PRINT ≥ 2) -

Unsteady aerodynamics are computed in the preface phase of ASTROS*. The Aerodynamic Influence Coefficient (AIC) matricies are computed once and for all in this preface phase, before any ASTROS* optimization and/or analysis takes place. Flutter and trim analyses can then be performed using the saved AIC's (note: one AIC is generated for each M-k pair specified by the **MKAEROZ** bulk data card(s)) since the resulting unsteady pressures due to flexible structural mode shapes are a curvefit (linear, quadratic or cubic, specified in the **FLUTTER** bulk data card) of the rigid body mode results.

6.4.1 Rigid Body Modes

Unsteady pressure results for three rigid body modes (for both symmetric and anitsymmetric cases) are always generated by ZAERO if the aerodynamic model is symmetric about the X-Z plane (i.e. if XZSYM is "YES" in the **AEROZ** bulk data card). For cases where XZSYM is set to "NO", asymmetric rigid body modes are generated. Results for all Mach number and reduced frequency pairs specified by **MKAEROZ** bulk data card(s) are output. This output is extremely useful in checking the robustness of the resulting aerodynamics.

For example, unsteady pressures along lifting surface strips can be examined for "smoothness". "Spikey" pressures can occur if not enough chordwise boxes are used to adequately capture the reduced frequency input (see modeling guidelines). Also, stability derivatives can be verified from computed generalized forces, e.g.

$$C_{L_\alpha} = \frac{\text{Real}\left(Q_{12}\right)}{S} \quad \text{or} \quad C_{M_\alpha} = \frac{\text{Real}\left(Q_{22}\right)}{S\,c}, \text{ etc.}$$

where Q_{ij} are the generalized aerodynamic forces, S = planform area, and c = reference chord length.

The three rigid body modes are:
MODE 1 = forward-backward translation along the x-axis (freestream direction)
MODE 2 = up-down translation along the z-axis (plunging mode)
MODE 3 = pitching motion about the reference GRID point specified by GREF in the **AEROZ** bulk data card (pitching mode)

Rigid body mode unsteady pressures and generalized aerodynamic forces are computed for each reduced frequency specified in the **MKAEROZ** bulk data card(s).

-- Symmetric Analysis

```
SYMMETRIC ANALYSIS FOR 3 RIGID BODY MODES AT M= 0.800 K= 0.001 REFERENCE LENGTH=( 200.00000/2.0)
MODE 1:FORWARD-BACKWARD ALONG X. MODE 2: PLUNGING ALONG  Z. MODE 3: PITCH UP ABOUT (X,Y,Z)=    0.00     0.00     0.00
  UNSTEADY CP FOR THREE RIGID BODY MODES
 INTERNAL ID EXTERNAL ID      RE(CP1)      IM(CP1)      RE(CP2)      IM(CP2)      RE(CP3)      IM(CP3)
           1         100 -0.3320E-08 -0.1222E-04 -0.2157E-08 -0.1513E-04  0.1513E+01 -0.1451E-02
           2         101 -0.3320E-08 -0.1221E-04 -0.8489E-09 -0.6254E-05  0.6254E+00 -0.5954E-03
           3         102 -0.3320E-08 -0.1221E-04  0.8558E-09  0.6288E-05 -0.6288E+00  0.5992E-03
           4         103 -0.3320E-08 -0.1220E-04  0.2161E-08  0.1515E-04 -0.1515E+01  0.1453E-02
           5         104 -0.4388E-08 -0.6749E-05 -0.1380E-08 -0.1674E-04  0.1674E+01 -0.1300E-02
                                                              .
                                                              .
                                                              .

GENERALIZED AERODYNAMIC FORCES OF THREE RIGID MODES
        MODE      RE(Q1)       IM(Q1)       RE(Q2)       IM(Q2)       RE(Q3)       IM(Q3)
           1 -0.5037E-05 -0.5134E-02  0.3259E-08  0.1536E-04 -0.1536E+01  0.1314E-02
           2 -0.8031E-08 -0.8874E-03  0.3758E-05 -0.1672E+00  0.1672E+05  0.1430E+02
           3  0.4364E-06  0.5112E-01  0.5099E-02  0.1564E+01 -0.1564E+06 -0.1088E+03
```

-- Antisymmetric Analysis

```
ANTI-SYMMETRIC ANALYSIS FOR 3 RIGID BODY MODES AT M= 0.800 K= 0.001 REFERENCE LENGTH=( 200.00000/2.0)
MODE 1:LATERAL MOTION ALONG Y. MODE 2: ROLLING ABOUT  X. MODE 3: YAWINIG ABOUT (X,Y,Z)=    0.00     0.00     0.00
  UNSTEADY CP FOR THREE RIGID BODY MODES
 INTERNAL ID EXTERNAL ID     RE(CP1)      IM(CP1)      RE(CP2)      IM(CP2)      RE(CP3)      IM(CP3)
          1          100  0.2493E-09  0.6174E-05 -0.9988E-08 -0.4582E-07  0.6174E+00 -0.5441E-03
          2          101  0.6015E-09  0.1490E-04  0.5920E-09 -0.9334E-08  0.1490E+01 -0.1313E-02
          3          102  0.6008E-09  0.1489E-04 -0.5940E-09  0.1333E-06  0.1489E+01 -0.1312E-02
          4          103  0.2487E-09  0.6167E-05  0.9997E-08  0.9683E-07  0.6167E+00 -0.5434E-03
          5          104 -0.1750E-09  0.6793E-05 -0.5010E-08 -0.1932E-06  0.6793E+00 -0.4744E-03
                                                        .
                                                        .
                                                        .

 GENERALIZED AERODYNAMIC FORCES OF THREE RIGID MODES
        MODE     RE(Q1)       IM(Q1)      RE(Q2)       IM(Q2)       RE(Q3)       IM(Q3)
           1  0.5044E-04 -0.1300E-01 -0.1005E-04 -0.2708E-01 -0.1300E+04 -0.5870E+01
           2  0.1377E-08  0.8035E-07 -0.1390E+00 -0.4057E+03  0.7271E-02 -0.1327E-03
           3  0.1008E-02  0.2538E+01 -0.6466E-03 -0.1528E+01  0.2538E+06 -0.1463E+03
```

Mode #1 **Mode#2** **Mode#3**

MACH	=	Free stream Mach number
K	=	Reduced frequency defined as $k = \omega(\text{REFC}/2)/V_\infty$ and specified in the **MKAEROZ** bulk data card(s)*
REFERENCE LENGTH	=	Reference length used for the reduced frequency definition, i.e. REFC/2*
INTERNAL ID	=	Aerodynamic box internal identification number
EXTERNAL ID	=	Aerodynamic box external identification number
RE(CPi), IM(CPi)	=	Real and imaginary components, respectively, of the unsteady pressure for the i'th mode

* REFC is the reference chord length defined in the **AEROZ** bulk data card

---

6.4.2 Flexible Modes

Flexible mode unsteady pressures and generalized aerodynamic forces are computed for each reduced frequency specified in the **MKAEROZ** bulk data card(s). The number of modes computed and output is equal to the number of modes retained in the modal analysis (i.e. based on the value of ND in the **EIGR** or **EIGC** bulk data card input).

```
UNSTEADY PRESSURE AT REDUCED FREQUENCY =   0.00100 MACH NUMBER =   0.80000 FOR    5 MODES, COMPUTED BY LINEAR METHOD

  INT ID      RE(CP)       IM(CP)       RE(CP)       IM(CP)       RE(CP)       IM(CP)       RE(CP)       IM(CP)       RE(CP)       IM(CP)
                   1            1            2            2            3            3            4            4            5            5
       1 -0.1666E-03  0.9323E-06 -0.2359E-03  0.1354E-05 -0.1548E-03  0.1049E-05  0.1289E-05 -0.5067E-06  0.1124E-03 -0.1130E-05
       2 -0.6888E-04  0.3844E-06 -0.9755E-04  0.5779E-06 -0.6401E-04  0.4247E-06  0.5393E-06 -0.7033E-07  0.4645E-04 -0.3332E-06
       3  0.6923E-04 -0.3865E-06  0.9805E-04 -0.5809E-06  0.6433E-04 -0.4270E-06 -0.5372E-06  0.7092E-07 -0.4669E-04  0.3355E-06
       4  0.1668E-03 -0.9335E-06  0.2362E-03 -0.1355E-05  0.1550E-03 -0.1051E-05 -0.1289E-05  0.5075E-06 -0.1125E-03  0.1132E-05
       5 -0.2420E-03  0.1141E-05 -0.3404E-03  0.1663E-05 -0.2224E-03  0.1260E-05  0.1502E-04 -0.8457E-07  0.1475E-03 -0.4169E-06
                                                                       .
                                                                       .
                                                                       .
                                          4QIJ         MATRIX TYPE=COMPLEX DOUBLE PRECISION
```

Mode Numbers

Q11 **Q21** **Q31**

```
                             1                       2                       3                       4                       5
1   -2.1250E+01  1.2259E-02 -3.9363E+01  8.7132E-03 -3.3416E+01  3.2613E-02 -3.0415E+01 -4.7214E-02  1.1056E+02  1.2971E-01
2    2.9480E+01  2.8217E-02  3.4632E+01  5.1553E-03  3.4127E+01  2.5082E-02 -6.5590E+00 -2.2704E-02  1.7129E+01  1.9265E-02
3    3.8185E+01  3.6133E-02  4.9455E+01  2.8088E-02  4.7057E+01  8.7403E-04  3.5309E+00  2.5383E-02  1.1347E+00  1.0430E-02
4   -2.7629E+00  6.6542E-03 -1.4895E+00  7.8721E-03 -1.5436E+00  9.3729E-03  2.0483E+01 -6.7446E-04 -1.3897E+00  1.7131E-02
5    1.5522E+01 -8.2547E-03  1.9105E+01 -1.5540E-02  5.1638E+00 -2.0632E-02 -9.7818E+00 -3.3675E-02  4.3557E+01 -7.1003E-02
```

Real **Imaginary**

MACH NUMBER = Free stream Mach number

RE(CP), IM(CP) = Real and imaginary component of pressure, respectively

---

6.5 K Method Flutter Results

- Output generated by **FLUTTER** (METHOD = K or PKK) -

K method flutter results can be requested by setting METHOD in the **FLUTTER** bulk data card to K or PKK. The K method should be used to verify the PK flutter results. The number of modes computed by the K flutter method is equal to the number of modes retained in the modal analysis (i.e. based on the value of ND in the **EIGR** or **EIGC** bulk data card input).

Important Note: The K method should only be used for analysis and not for optimization since the method itself does not yield true aerodynamic damping. Database entities containing flutter damping results are, therefore, not updated with the K method results.

S U M M A R Y   O F   K   F L U T T E R   E V A L U A T I O N

MODE = 1   MACH NUMBER = 0.8000   DENSITY RATIO = 1.0000E+00

		VELOCITY		DAMPING	FREQUENCY		COMPLEX EIGENVALUE	
NO	V/BW	EQUIVALENT	TRUE	RATIO	CYC/SEC	RAD/SEC	REAL	IMAGINARY
1	0.00	0.000000E+00	0.000000E+00	0.000000E+00	4.460721E+00	2.802754E+01	0.000000E+00	0.000000E+00
2	1.00	2.837067E+03	2.837067E+03	-6.489850E-02	4.515332E+00	2.837067E+01	1.242398E-03	-8.062979E-05
3	1.11	3.162377E+03	3.162377E+03	-7.221635E-02	4.529772E+00	2.846140E+01	1.234490E-03	-8.915037E-05
4	1.25	3.574543E+03	3.574543E+03	-8.166450E-02	4.551250E+00	2.859635E+01	1.222866E-03	-9.986476E-05
5	1.43	4.115229E+03	4.115229E+03	-9.459399E-02	4.584713E+00	2.880660E+01	1.205080E-03	-1.139933E-04
6	1.67	4.859589E+03	4.859589E+03	-1.137758E-01	4.640565E+00	2.915753E+01	1.176247E-03	-1.338284E-04
7	2.00	5.962561E+03	5.962561E+03	-1.463319E-01	4.744855E+00	2.981280E+01	1.125108E-03	-1.646392E-04
8	2.38	7.353303E+03	7.353303E+03	-1.984824E-01	4.915321E+00	3.088387E+01	1.048423E-03	-2.080935E-04
9	2.50	7.828461E+03	7.828461E+03	-2.206042E-01	4.983753E+00	3.131385E+01	1.019829E-03	-2.249785E-04
10	2.78	9.037170E+03	9.037170E+03	-2.920511E-01	5.177917E+00	3.253381E+01	9.447789E-04	-2.759237E-04
11	2.94	9.814847E+03	9.814847E+03	-3.530426E-01	5.311077E+00	3.337048E+01	8.979974E-04	-3.170314E-04
12	3.12	1.072294E+04	1.072294E+04	-4.404190E-01	5.461150E+00	3.431342E+01	8.493213E-04	-3.740572E-04
13	3.33	1.175100E+04	1.175100E+04	-5.546603E-01	5.610689E+00	3.525300E+01	8.046516E-04	-4.463083E-04
14	3.57	1.290848E+04	1.290848E+04	-6.919158E-01	5.752454E+00	3.614374E+01	7.654800E-04	-5.296477E-04
15	3.85	1.424419E+04	1.424419E+04	-8.534758E-01	5.894288E+00	3.703490E+01	7.290839E-04	-6.222555E-04
16	4.00	1.500292E+04	1.500292E+04	-9.458866E-01	5.969473E+00	3.750731E+01	7.108342E-04	-6.723685E-04
17	4.17	1.583968E+04	1.583968E+04	-1.048456E+00	6.050312E+00	3.801523E+01	6.919659E-04	-7.254959E-04
18	4.35	1.677122E+04	1.677122E+04	-1.163832E+00	6.139212E+00	3.857381E+01	6.720707E-04	-7.821771E-04
19	4.55	1.781921E+04	1.781921E+04	-1.295541E+00	6.239232E+00	3.920225E+01	6.506957E-04	-8.430028E-04
20	1000.00	2.247042E+05	2.247042E+05	-1.955762E+00	3.576279E-01	2.247043E+00	1.980512E-01	-3.873408E-01

MODE = 2   MACH NUMBER = 0.8000   DENSITY RATIO = 1.0000E+00

		VELOCITY		DAMPING	FREQUENCY		COMPLEX EIGENVALUE	
NO	V/BW	EQUIVALENT	TRUE	RATIO	CYC/SEC	RAD/SEC	REAL	IMAGINARY
1	0.00	0.000000E+00	0.000000E+00	0.000000E+00	1.055601E+01	6.632539E+01	0.000000E+00	0.000000E+00
2	1.00	6.402727E+03	6.402727E+03	-5.454512E-02	1.019026E+01	6.402727E+01	2.439328E-04	-1.330534E-05
3	1.11	7.050913E+03	7.050913E+03	-5.695889E-02	1.009969E+01	6.345822E+01	2.483272E-04	-1.414444E-05
4	1.25	7.835391E+03	7.835391E+03	-5.886756E-02	9.976330E+00	6.268313E+01	2.545064E-04	-1.498217E-05
5	1.43	8.795870E+03	8.795870E+03	-5.945781E-02	9.799343E+00	6.157109E+01	2.637827E-04	-1.568394E-05
6	1.67	9.978459E+03	9.978459E+03	-5.636850E-02	9.528727E+00	5.987076E+01	2.789783E-04	-1.572559E-05
7	2.00	1.141154E+04	1.141154E+04	-4.216917E-02	9.081017E+00	5.705772E+01	3.071646E-04	-1.295288E-05
8	2.38	1.267854E+04	1.267854E+04	-4.806762E-03	8.474977E+00	5.324986E+01	3.526657E-04	-1.695180E-06
9	2.50	1.298812E+04	1.298812E+04	1.383525E-02	8.268494E+00	5.195248E+01	3.704994E-04	5.125950E-06
10	2.78	1.357605E+04	1.357605E+04	7.793012E-02	7.778504E+00	4.887378E+01	4.186471E-04	3.262522E-05
11	2.94	1.388858E+04	1.388858E+04	1.337371E-01	7.515483E+00	4.722117E+01	4.484628E-04	5.997611E-05
12	3.12	1.430753E+04	1.430753E+04	2.128746E-01	7.286766E+00	4.578410E+01	4.770574E-04	1.015534E-04
13	3.33	1.494122E+04	1.494122E+04	3.141358E-01	7.133905E+00	4.482365E+01	4.977205E-04	1.563518E-04
14	3.57	1.584784E+04	1.584784E+04	4.328031E-01	7.062334E+00	4.437395E+01	5.078597E-04	2.198032E-04
15	3.85	1.705374E+04	1.705374E+04	5.692071E-01	7.056886E+00	4.433972E+01	5.086442E-04	2.895239E-04
16	4.00	1.778252E+04	1.778252E+04	6.459706E-01	7.075438E+00	4.445629E+01	5.059803E-04	3.268484E-04
17	4.17	1.860809E+04	1.860809E+04	7.302684E-01	7.107767E+00	4.465942E+01	5.013879E-04	3.661478E-04
18	4.35	1.954530E+04	1.954530E+04	8.240550E-01	7.154680E+00	4.495418E+01	4.948343E-04	4.077707E-04
19	4.55	2.061352E+04	2.061352E+04	9.299726E-01	7.217636E+00	4.534974E+01	4.862396E-04	4.521896E-04
20	1000.00	2.253742E+05	2.253742E+05	1.959593E+00	3.586943E-01	2.253743E+00	1.968754E-01	3.857956E-01

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MODE = Mode shape number
MACH NUMBER = Free stream Mach number
DENSITY RATIO = Density ratios used to scale the value of RHOREF defined in the **AEROZ** bulk data card. The density used in the flutter analysis can be computed from

$$\rho = \text{RHOREF} \times \text{DENSITY RATIO} \quad \text{where DENSITY RATIO} = \frac{\rho}{\rho_{sea\ level}}$$

NO = Index counter of reduced frequency
V/BW = Equal to 1/reduced frequency for all reduced frequencies input in the corresponding **MKAEROZ** bulk data card (i.e. $1/k = V/BW$, where V=velocity, B=REFL=referecne length, W=ω=circular frequency)
VELOCITY
EQUIVALENT = Equivalent airspeed
TRUE = True airspeed

$$V_{EQUIVALENT} = V_{TRUE} \times \sqrt{\text{DENSITY RATIO}}$$

DAMPING RATIO = Aerodynamic damping (g) computed from $g = Im(\lambda)/Re(\lambda)$, where λ = computed eigenvalue. Note: Unlike the P-K method of flutter analysis, the magnitude of the aerodynamic damping term resulting from the K-method flutter solution does not accurately reflect the true aerodynamic damping of the structure, except near the flutter crossing point (i.e. near g=0). The K-method does however accurately predict both the flutter crossing point (where g=0) and whether the aerodynamic structure is stable (g<0) or unstable ($g\geq0$) at given velocities.
FREQUENCY = Structural natural frequency under aerodynamic loading at given reduced frequency given in both (CYC/SEC) cycles per second and radians per second. Computed from $\omega = 1/\sqrt{Re(\lambda)}$, where λ = computed (RAD/SEC) eigenvalue.
COMPLEX
EIGENVALUE = Computed complex eigenvalue from the equation:

$$\left| [M] + \frac{1}{2}\rho\frac{L^2}{k^2}[Q] - \lambda\left[\omega_n^2\right][M] \right| = 0$$

where

$[M]$ = the generalized mass matrix
ρ = air density
L = reference length (REFC)
k = reduced frequency
$[Q]$ = the aerodynamic generalized force matrix
ω_n = natural frequency
λ = eigenvalues to be computed

Flutter crossings (where g=0) are printed in tabular format as shown below. Crossing for each mode as a function of assumed structural damping are generated. This table allows the user to "gauge" the strength of any flutter crossing. As an example, if 2% structural damping is assumed for a given configuration and only the first term appears under G=0.0 for a particular mode, then it can be assumed that the structure posses enough structural damping to prevent the onset of flutter. For the case shown below, strong flutter beyond 4% structural damping occurs on modes 2 and 4, but both computed flutter speeds are well beyond the input flight Mach number of 0.8 (12,758 in/s = Mach 0.95 and 34,100 in/s = Mach 2.55 at sea level density). For this reason, it can be assumed that no flutter will occur for this configuration at M=0.8. A flutter match point occurs when the computed Mach number equals the input Mach number. In the event the computed Mach number is less than the input Mach number, the matchpoint can be found by varying the density to simulate higher altitudes.

MACH NUMBER = 0.8000   DENSITY RATIO = 1.0000E+00

FLUTTER SPEED (EQUIVALENT) /
FREQUENCY (HERTZ)   AS A FUNCTION OF THE ASSUMED STRUCTURAL DAMPING

MODE	G = 0.0%	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%
2	12758.4/ 8.422	12841.4/ 8.366	12924.4/ 8.311	12998.8/ 8.260	13044.7/ 8.221	13090.5/ 8.183	13136.4/ 8.145	13182.3/ 8.107	13228.1/ 8.068
4	34100.3/ 25.575	34457.1/ 25.451	34813.9/ 25.327	35170.7/ 25.202	35527.5/ 25.078	35884.2/ 24.954	36241.0/ 24.829	36597.8/ 24.705	37150.9/ 24.527

Flutter Speeds

Flutter Frequencies

To provide the user a quick means of viewing the flutter results, flutter plots of frequency and damping versus velocity are printed. Modes are displayed alphabetically, i.e. A=Mode 1, B=Mode 2, etc. Velocity axes are scaled by the value printed next to the velocity label, e.g. for the example shown, the point on the velocity axis labeled 500 represents a velocity of 500 x 6.600E+01 = 33,000 in/s.

Frequency versus Velocity Plot

```
                                                                               DENSITY RATIO =  1.0000E+00

                  * * * *  F R E Q U E N C Y   V E R S U S   V E L O C I T Y  * * * *
400.0 +
      I
      I
      I
      I
      I
      I
      I
      E                                                            E
300.0 +                                                                   E       E         E            E
      I                                                                                                                  E
      I
      I
      I
      I
      I
      I
200.0 D
      I                                      C   C  C
      C                                   D               C
      I                                       D   D   D      D  C
      I                                                                D        C
      I                                                                         D DC    D  C
      I                                                                                    D  DC D C   C
      I                                                                                              D  D  C    C C   C   C
      I                                                                                                 DD D
      I                                                                                                      D
100.0 +
      I
      I
      B
      I             BB B B B  B
      I                        BBBBB            B
      I                       A A A A A A AB B
      A     AAA A A  AA A AA
      I
      I
  0.0 +-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+-----------+----------
-+
      0          100         200         300         400         500         600         700         800         900
1000
                                              VELOCITY ( X 6.600E+01 )
```

Damping versus Velocity Plot